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COMPUTER MANAGEMENT OF A COMBINED SEWER SYSTEM

Seattle Metropolitan Municipality

PREPARED FOR
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C. P. Leiser

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16. ABSTRACT At the conclusion of a ten-year construction program which affected much of Seattle's combined sewer system, a computer-controlled "total systems management" complex was proposed, funded and constructed. Computer augmented treatment and disposal (CATAD) takes advantage of storage in the sewers to limit overflows, and selects overflow points based on water quality data.

Since the control system began operating in 1971, receiving water quality, especially dissolved oxygen and coliform levels, has shown significant improvement; overflow volume has decreased by 50 to 60 percent during supervisory control and in excess of 90 percent during three months of limited automatic control. Eight pollution loading parameters were measured and found to be 68 percent less than before advanced control techniques.

Capital costs totaled $2.6 million for the control system at the 36 remote stations, or $5.3 million, including construction of 15 gate-driven regulator stations. Annual maintenance and operation costs totaled $270,000. The system is worth roughly $40 to $245 million in equivalent sewer separation.

Work continues on a fully automatic optimizing model to add predicative capability to program decisions so the system could maintain an 80 percent overflow reduction.

(See also W 72-08984)(EPA)

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COMPUTER MANAGEMENT OF A COMBINED SEWER SYSTEM

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

One source of water contamination has been sewer overflows occurring during rainfalls. This report describes a computer-controlled "total systems management" complex designed to reduce combined sewer overflows by providing the controls that permit storing the overflow in sewers.

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Director
National Environmental
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ABSTRACT

At the conclusion of a ten-year construction program which affected much of Seattle's combined sewer system, a computer-controlled "total systems management" complex was proposed, funded and constructed. CATAD takes advantage of storage in the sewers to limit overflows, and selects overflow points based on water quality data.

Since the control system began operating in 1971, receiving water quality, especially dissolved oxygen and coliform levels, has shown significant improvement; overflow volume has decreased by 50-60 percent during supervisory control, and in excess of 90 percent during three months of limited automatic control. Eight pollution loading parameters were measured and found to be 68 percent less than before advanced control techniques.

Capital costs totaled $2.6 million for the control system at the 36 remote stations, or $5.3 million, including construction of 15 gate-driven regulator stations. Annual maintenance and operation costs total $270,000. The system is worth roughly $40-$245 million in equivalent sewer separation.

Work continues on a fully automatic optimizing model to add predicative capability to program decisions so the system could maintain an 80 percent overflow reduction.

This report was submitted in fulfillment of Project Number 11022 ELK, by the Municipality of Metropolitan Seattle, under the sponsorship of the Environmental Protection Agency. Work was completed as of August 1973.

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SECTION I

CONCLUSIONS

1. A 13,120 acre combined sewer area within the city of Seattle has become an example of a successful application of advanced computer control techniques to reduce combined sewer overflows. Fifteen regulator stations and one major pumping station were controlled to reduce overflow volumes by 50 to 60 percent under supervisory control, and in excess of 90 percent under automatic program control and during unusually dry weather.

2. Loading analysis reveals that 80 to 90 percent of the peak loading has been reduced, and the peak loading has been shifted to a higher rainfall rate which occurs less frequently. Total loading in pounds has been decreased an average of 58 percent for ammonia; up to 76 percent for COD. The average loading reduction for eight measured pollutant factors was 68 percent.

3. A total of 514 storms and 762 overflow events were analyzed. Rainfall studies show that the city averaged about 150 measurable storms per year at an average of 0.23 inches per storm. The weather studies also indicated that in the final year of automatic control, rainfall volume was 50 percent below normal; however, the number of storms remained approximately the same.

4. A few intense storms during summer periods severely influenced the performance data. Further studies are necessary to determine whether system performance was actually as ineffective during summer periods as the limited data indicated. Additional data may contradict the information accumulated during this study, which indicates that the system was most effective during winter storms. This may be due to the inability of local control systems to recognize storm or collection system conditions outside of the stations' immediate area.

5. During this period of regulator local control, the tendency was for infrequent but large volume overflows. Supervisory and advanced storm control strategies allow for regular monitor-analysis-command cycles. It was found that frequent, short duration, small volume overflows shaved storm flow peaks and resulted in an impressive reduction in total system overflow volumes.

6. Rainfall intensity has a considerable effect on overflows. Considering the average rainfall rate of a storm, the total system reduced overflow volumes by 73.6 percent in supervisory control, 97.2 percent in automatic control, and 85.8 percent under combined advanced control modes.

7. The many variables which influence the overflow quantity generated by a system during a given storm make standard statistical correlations very difficult. Tabular analysis of overflow events for different rainfall ranges was quite successful as was a moving average program which effectively indicated loading trends.

8. In analyzing a specific sample station, a characteristic time lag, build up and wash-out was observed for all measured pollutants (often termed the first flush effect). However, the peak concentrations for some pollutants such as ammonia evidenced no obvious relationship with the more typical solids analysis pattern during a storm.

9. Each station tended to show a "fingerprint" effect for sequential overflow data. This fingerprint was generally unique for each station and usually repeated itself for different storm types. The data indicated that the first flush of materials is often diverted to the interceptor in a combined system rather than overflowing to the receiving water.

10. Overflow priorities were based primarily upon volume reduction. Station by station priority varied considerably depending on which pollution factor was the basis for establishing priority.

11. During the course of the study, the Duwamish River receiving water has improved dissolved oxygen content by 1 to 2 milligrams per liter.

12. During the supervisory control period, coliform counts in the Elliott Bay area have dropped significantly at all near-shore stations, but have remained relatively constant at offshore stations. Coliform counts in the Duwamish River have fallen more than 50 percent in the estuary area where overflows generally occur.

13. The success of the computerized control management system is due to:

    (a) surveillance and early attention to potential mechanical and control problems,

    (b) early action and preparation for storm events,

    (c) logical use of all available system storage to minimize combined sewer overflows.

14. System cost was $2.6 million for the computer controls and station control equipment. Additional regulator station construction would increase costs to $5.3 million.

15. Capital costs averaged about $200 per acre; maintenance and operation costs averaged $5 per acre or $.88 per thousand gallons of overflow captured and diverted to the treatment plant.

16. Interfacing was the most difficult hardware problem encountered. About two years of sporadic work were required to pinpoint and solve electrical noise interference problems.

17. Equivalent costs for complete separation to equal the CATAD system volume reduction is between 40 million and 240 million dollars. Separation does eliminate overflows compared to CATAD's 60 - 90 reduction, however, separation also diverts many nutrients and other pollutants into receiving waters effectively lowering the performance of separation to a level with the CATAD system. (Editor's Note: This comment is also made in Table 49).

18. Intangible benefits include the newly available routine data processing capability, a flexible system readily adaptable to new requirements or expanded facilities, possible improved plant operation and capacity by controlling dry weather flows, improvements to receiving water, improved public relations, and the possibility of delaying or preventing the large cost of sewer separation.

19. Data transmission checking and protection features are necessary. Local control capability and 24-hour monitoring must assure that breakdowns in any portion of the system are covered in some manner.

20. The storage rule curve control technique is feasible and has been very effective on this control system.

21. It is often difficult to isolate system problems to either hardware or software. A systematic problem solving technique using the computer as a diagnostic tool effectively isolated such problems.

22. Excessively rapid equipment reaction to level changes risks creating a water hammer or other potentially dangerous and expensive problem within the collection system.

SECTION II

RECOMMENDATIONS

1. Development of a computerized control system necessitates passing through various levels of control. A flexible, informative console is essential during the developmental phase to provide system information and to allow a human operator to perform control functions and enlarge the control data base.

2. To minimize hardware/software problems, a single contractor should be selected for complex computer control systems wherever possible.

3. Studies should be initiated to predict overflow water quality, and to minimize pollutant loading factors.

4. The first flush capture in combined sewer systems versus storm drains should be examined. Sequential samplers located at the site of a trunk diversion and overflow point should be triggered automatically and remotely by a computer system if possible.

5. New control systems should make maximum use of digital sensors to provide data for direct transmission to the central computer. Modern noise filtering techniques should be applied to minimize transmission and/or command difficulties.

6. When installing a CATAD-like control system, early data collection and instrument calibrations should be specified to eliminate one major source of errors.

7. Urban drainage studies should be continued to determine how loading changes from separated and urban areas affect regulator performance.

8. The performance characteristics of Michigan and Brandon Regulators where the sewer profile has been modified to drain stagnant sewage back to the interceptor after an overflow should be studied.

9. Summer storm response to the advanced control system should be studied further to determine whether the unimpressive performance is to be expected or is a result of unusual storm activity during the automatic control period.

10. More definitive methods of classifying storms should be made available to simplify analysis of regulator and system performance to various storm characteristics.

11. Improvement resulting from the optimizing simulation model being developed by Metro Seattle should be monitored. It's effectiveness as a design tool in determining runoff coefficients and selecting optimum storage volumes should be determined.

12. The effect and performance of sewer separation of North Interceptor and West Point Plant flows should be evaluated and compared with centralized control influence on the Elliott Bay interceptor.

13. Standardized data collection, display hardware and software would greatly reduce costs in developing similar computer control systems.

14. Investigate the possibility of an intertie between the collection system control model and the Duwamish River Estuary model in determining overflow priorities.

15. Standardized sampling equipment should be improved to avoid data gaps which are a major deterent to thorough analysis of all storm and control situations.

16. Software development should follow a logical sequence to minimize delays:

    a. System design
    b. Systems programming
    c. Applications programming

17. A thorough information and training program should be initiated as early as possible. The training program should be run con-currently with the development, and should include all documentation and standardized operator's manuals.

18. Strong and continued leadership and staff support are required to successfully complete a major research and development project such as the CATAD system.

19. Federal and/or State guidance in the form of overflow pollutant guidelines or limitations would be beneficial in determining overflow priorities in automated control systems where alternative overflow decisions are consistent and can be easily programmed.

SECTION III

INTRODUCTION TO THE SYSTEM

SYSTEMS IN GENERAL

Computer proliferation, significant improvements in output capacity versus investment, and the success of computer techniques in complex and varied applications around the country have brought the term "systems" into common use. In recent years, urban analysts and experts have advocated management information systems and the use of systems analysis and planning-programming-budgeting in city governments. Analysis of whole systems rather than their individual components is becoming increasingly popular in many fields including pollution control (1). Systems methodology, also referred to as management science, operations research, systems analysis, and systems engineering is an analytical approach for large, complex, multi-variable problems. The technique provides systematic definition and evaluation of alternative solutions to these complex problems for use by decision makers. Even a superficial review of the literature reveals that pollution control and other environmental quality problems are complex enough to benefit by the systems approach (2). Insights thus gained may lead to much better problem solutions. Large, complex, multi-dimensional problems are not new, but they could not be clearly pictured even a decade ago. Rules of thumb and handbook criteria were used to design and operate water pollution control facilities. In the past decade, technology has changed those standards. New mathematical, economic and computational tools demonstrate the fallibility of earlier design criteria. Today's methodologies and computer technology analyze many variable and relevant factors to determine engineering design and operating specifications. This then, is the systems approach.

Hierarchical management levels of all organization structures require four basic levels of information for operating an organization as identified by Tolle (3).

1. Policy or strategic information -- is required at top management levels for defining priorities.

2. Planning and forecast information -- is required or initiated by middle management to identify prospective avenues for future undertakings.

3. Performance or control information -- is required by direct supervisory personnel to determine how well objectives are being met.

4. Operations, production, transactions or working information -- is required for instruction of or initiated by workers directly involved with the organization's tasks.

The tremendous information volumes and levels of refinement have led to the use of the computer based management information system (MIS) in many industries. Evolution of these intelligence systems can be compared to development of human intelligence. The basic decision process includes four identifiable stages of activity:

1. Observation
2. Inference
3. Evaluation
4. Choice.

Management information systems generally evolve from relatively simple data banks where observations are summarized so that a user can apply inference and evaluation to make a decision. A second stage data bank system involves the computer in making inferences so that a manager can propose "what if" questions and receive an array of responses for his evaluation and decision. A third level is often a large scale optimization model system which encompasses action recommendation. Procedures are programmed to evaluate alternatives against assigned goals. The manager either implements a decision based on the recommendation or he rejects the alternative and requests further analysis for decision. In the final stage of maturity, the entire decision process is automated within the information system. Observation, the ability to choose to initiate action, commit resources and monitor results are programmed into operating procedures. The complexity of the decision process for any given application limits the development of a fourth level (fully automated) system to very well defined environments (4).

Federal, State and local governments and other decision making bodies have shown increasing interest in modern systems techniques. The systems approach, however, has just begun to solve management problems in water pollution control. Although is has often demonstrated technical success, the results have frequently been rejected by the political process (2). Metropolitan engineering-economics systems analysis of all aspects of urban water resources has been found feasible (5), and comprehensive simulation models are being designed in many areas around the country. These systems methodologies produce simulation models which are static or dynamic mathematical representations of some process. Gordon (6) presents an excellent description of the model classifications now employed in systems studies. Simulation model sizes may vary from simply depicting the time-varying position of a stretched and released spring to the largest and most complicated dynamic environmental planning models in the country today (7). The water balance model, possibly a portion of the total environmental management model, is pictured by McPherson (2). The staggering amount of data to be collected, stored and evaluated in producing and running a model of this size dictates a computer based systems approach for either a one-time solution or for real-time process control.

"SYSTEMS CONCEPT" IN COMBINED SEWER REGULATION

Past and present applications of systems information and control techniques provide a wide base of experience which can be concentrated to apply systems concepts in combined sewer regulation and control. Combined sewer systems were designed and constructed on the principle that overflows at frequent locations could effectively provide prompt and local relief of collector sewers and interceptor lines. This concept resulted in a multiplicity of overflows and regulators, but also reduced the size of interceptors in various sections of the total sewer collection system. This "each unit of a sewer system for itself" concept does not integrate the various facilities into a master management plan. Defects of single unit control include:

1. Multiplicity of overflow points
2. Lack of priority sequence of locations to minimize environmental harm and hazards
3. Failure to achieve the full hydraulic capacities of each section of the total sewer system
4. Inability to utilize the whole sewer system in relation to the patterns of storm and runoff in various areas of a community; particularly large sewer areas with variable topography (8).

By including the full function of the combined sewer system control program, the manager can use the "systems concept" to achieve maximum benefits of regulator control. "Total systems management" of combined sewer systems uses not only the transporting capacity of sewer systems, but their retention capacity as well. Frequently, past improvement to a sewer facility in one location caused greater problems elsewhere in the system, but this fact was ignored due to the difficulty in analyzing and achieving total systems management. The concept envisions management or control of all elements and facilities of the sewer system to:

1. Maximize utilization of interceptor sewer capacity to carry combined sewage to the waste water treatment plant

2. Maximize utilization of all in-system storage

3. Give priority in the interceptor sewer to flows with a higher pollutional load whose overflow would result in adverse conditions upon receiving waters

4. Integrate use of combined sewer overflow storage or treatment facilities.

Communication is the key to a systems approach. Modern communication methods provide the basis for integrating the individual units into a master system. Avoid oversimplification of the systems concept in combined sewer system management and overflow control. Systems control dictates dynamic regulators so that facilities can efficiently route, limit, divert, transfer and store waste waters within the sewer system according to a predetermined plan. Measurement and status determination are accomplished by sensors which utilize electrical signals to represent such conditions as flow, head, pressure differences, gate positions and receiving water levels. Data collection, storage, correlation and display are accomplished by supervisory personnel or by computer programs they prepare. Decisions are executed by field crews or by remote control automation facilities which receive instructions and carry them out. These instructions are verified by feedback communication from field crews or automated communication channels.

Anticipating more stringent Federal controls on sewer overflows, numerous cities have begun or have implemented "total systems management" projects. In-depth descriptions of these control systems are available (8, 9, 10). Cleveland and Minneapolis/St. Paul have some type of supervisory control under consideration or now in operation, and an automatic control model is completed. Such models are difficult to lift off the drafting board and implement in actual hardware. Later sections of this report describe the country's most advanced fully automated feedback control system. In Seattle's Computer Augmented Treatment and Disposal System (CATAD), the human operator is an observer who is involved in the control loops only in the event of systems failures or unusual unprogrammable environmental conditions which require his specialized technical knowledge.

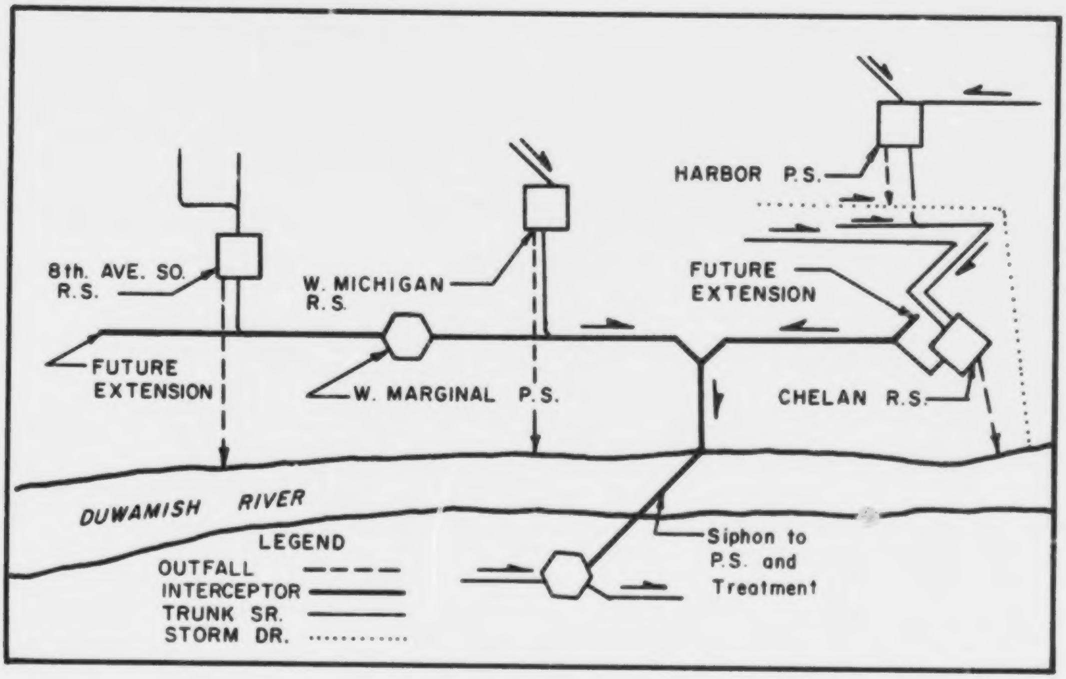
EVOLUTION OF SEATTLE DEMONSTRATION GRANT

Federal demonstration grants stimulated recent developments in computerized total systems management projects in combined sewer technology. Demonstration grants have a large impact on cities considering development of such control systems. Grigg (11) describes many positive and negative incentives available to and used by our government. Without the impetus and encouragement of Federal funding arrangements, Seattle and other cities might not have had the interest or funding to embark upon such research and development projects. Federal and State demonstration grant funding levels when this project began were considerably less than funds made available by the 1972 amendments to the Water Quality Act. Significantly, the money available in 1967 has provided six years of technological advancement in pollution control that might otherwise not be available for cities presently considering such systems.

When the Federal Water Pollution Control Administration (FWPCA) was formed in 1965, Seattle was already four years into a construction program to eliminate pollution of local receiving waters and to reduce overflows from a heavily overloaded combined sewer system. Design considerations and construction activities are discussed in the first major report on the CATAD system, "Maximizing Storage in Combined Sewer Systems" (12).

Computer system control of regulator storage within interceptor sewer lines was proposed by Metro early in 1966 in a request to the FWPCA for construction grant funding for an interceptor, regulator and pump system in the West Duwamish area of Seattle (Figure 1).

The agency denied Metro's request for construction funding for the regulator portion of that system, but expressed considerable interest in this type of construction. Later in 1966, public information about demonstration grants was widely distributed in the Federal Register (13). In October, 1966, a mutual resolution of the Metropolitan Council authorized application for a demonstration grant, and an application was submitted to the administrator of FWPCA. An FWPCA official visited Seattle and indicated interest in the project which had begun five years before with construction of an interceptor system with storage capacity. This official reviewed interceptor construction and three dynamic regulator structures with mechanically driven sluice gate mechanisms which had been operating for over three years. In November, 1966, FWPCA forwarded copies of demonstration grant application and guideline materials, and expressed interest in the program.



HARBOR P.S.
8th. AVE. SO. R.S.
W. MICHIGAN R.S.
FUTURE EXTENSION
FUTURE EXTENSION
W. MARGINAL P.S.
CHELAN R.S.
DUWAMISH RIVER
LEGEND
OUTFALL
INTERCEPTOR
TRUNK SR.
STORM DR.
Siphon to P.S. and Treatment

FIGURE 1

WEST DUWAMISH COLLECTION SYSTEM

Metro officials selected a technical consultant. A hydroelectric process control computer system in the Wenatchee, Washington, area was visited. Hydroelectric upstream water storage concepts from this and other control systems were applied to Metro's CATAD system control computer. Late in 1966 the exact details of the computer augmented treatment and disposal project were revised and resubmitted. In an official communication on December 29, 1966, the FWPCA commissioner extended the $1 million limitation for demonstration grant projects to the CATAD system. The grant offer was for $1,400,000 or 53.5 percent of the estimated eligible project costs.

To demonstrate changes in concept and costs since the original 1966 conception, some details of the demonstration grant request will be explained. Table 1 shows the breakdown of construction and services foreseen in the original estimate. Later additions to this breakdown outlined regulator construction costs of $1.5 million and water quality study expenses of $30,000. Primary features of the demonstration grant, agreed to by both parties, included:

Table 1. ORIGINAL GRANT COST ESTIMATES

	Total	Eligible
CONSTRUCTION		
65-11 (W. Duwamish Reg.'s)	$ 589,000	$ ---
Later Contracts-Construction*	1,550,000	1,550,000
Computer and Monitors	600,000	500,000
SUB-TOTAL	$2,739,000	$2,050,000
TECHNICAL SERVICES		
W. Q. Reports	$ 200,000	$ ---
Engineering Plans & Specs @ 6%	164,000	123,000
Supervision @ 3%	82,000	61,500
Post-Construction Studies	133,600	133,600
SUB-TOTAL	$ 579,600	$ 318,100
O & M (1 year)	$ 30,300	$ ---
Legal and Fiscal 1%	27,000	20,500
Administration 1%	27,000	20,500
Contingency 10%	274,000	205,000
Tax 4.2%	115,000	---
Site	100,000	---
SUB-TOTAL	$ 573,300	$ 246,000
GRAND TOTAL	$3,891,900	$2,614,100

*Later Contracts Detailed:

est.	Hanford	$ 450,000
	Lander	400,000
	Connecticut	250,000
	King	150,000
	Denny	300,000
		$1,550,000

Compared to Actual:

Harbor	$ 90,000
Chelan	75,000
Eighth	65,000
W. Michigan	60,000
	$290,000

1. Five automatic regulator stations
2. One computer control system
3. One central supervisory station
4. Water quality monitoring equipment
5. Controls and wiring for an automated CATAD storage and regulation system.

In one of the original submittals to the Federal Water Pollution Control Administration, the Metro staff predicted the sort of results expected from the CATAD control system. Table 2 summarizes this data and shows that the performance anticipated an optimistic 90 percent reduction in critical summertime overflows and a 77 percent reduction during the winter months, for an overall annual reduction of 80 percent overflows. In a later section, this report compares the predicted performance with actual results under different operating modes.

Table 2. PREDICTED CONTROL SYSTEM EFFICIENCIES

Rainfall Range Inches/Day	On Site Regulation Only									Computer Controlled Regulation								
	Winter			Summer			Annual			Winter			Summer			Annual		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
0.1 - 0.24	30	45	45	10	53	53	40	47	47	30	45	45	10	53	53	40	47	47
0.25 - 0.49	21	0	45	7	0	53	28	0	47	21	32	77	7	37	90	28	33	80
More than 0.5	14	0	45	2	0	53	17	0	47	15	0	77	2	0	90	17	0	80

A -- Number of Days

B -- Incremental Percentage of Overflows Contained

C -- Cumulative Percentage of Overflows Contained

Source: Table 3-9 "Metropolitan Seattle Sewerage and Drainage Survey" (27)

Note: Percentages based on statistical average days of rainfall in excess of 0.1 in/day which was: Summer - 19; Winter - 66; Annual - 88.

The original plan was for a three-year project beginning in January of 1967 with design, construction, evaluation and report breakdowns as shown in Figure 2. For reasons explained in later sections of this report, progress on the demonstration grant lagged behind schedule. In February of 1971, the demonstration grant was extended until August, 1973. The newer schedule (see Figure 3) called for an interim report describing progress to that date. This report, "Maximizing Storage in Combined Sewer Systems," was completed in 1972 and published late that year (12). These schedule extensions disrupted the 1967 budget plan because of additional maintenance, operation, administrative, engineering and programming expenses. Cost details are covered in detail in Section XI of this report.

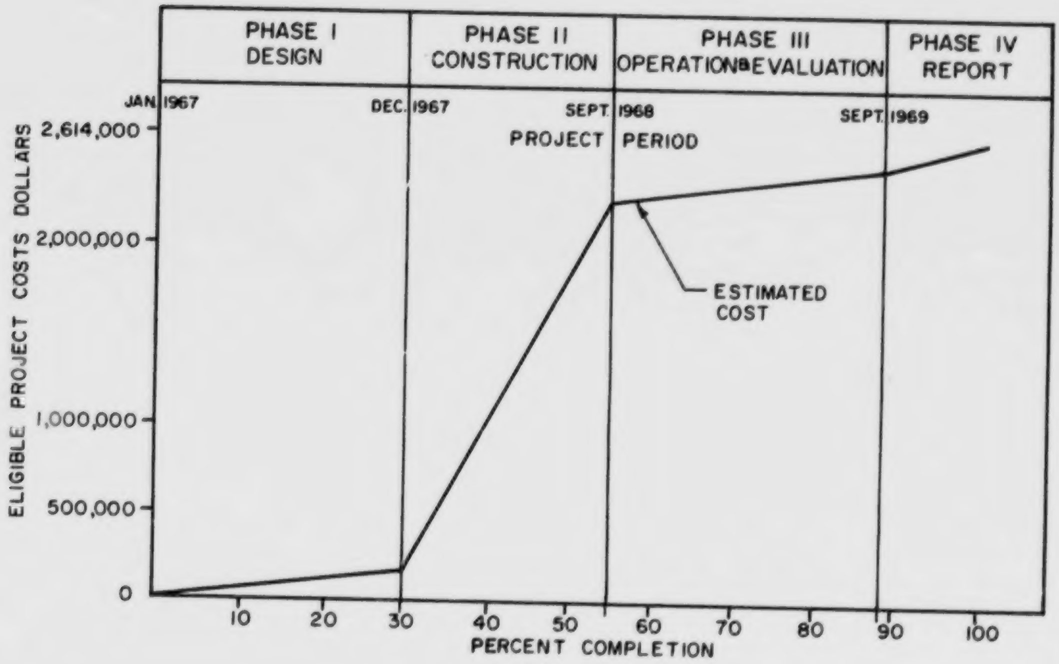


FIGURE 2

INITIAL PROJECT COSTS AND PLANNING

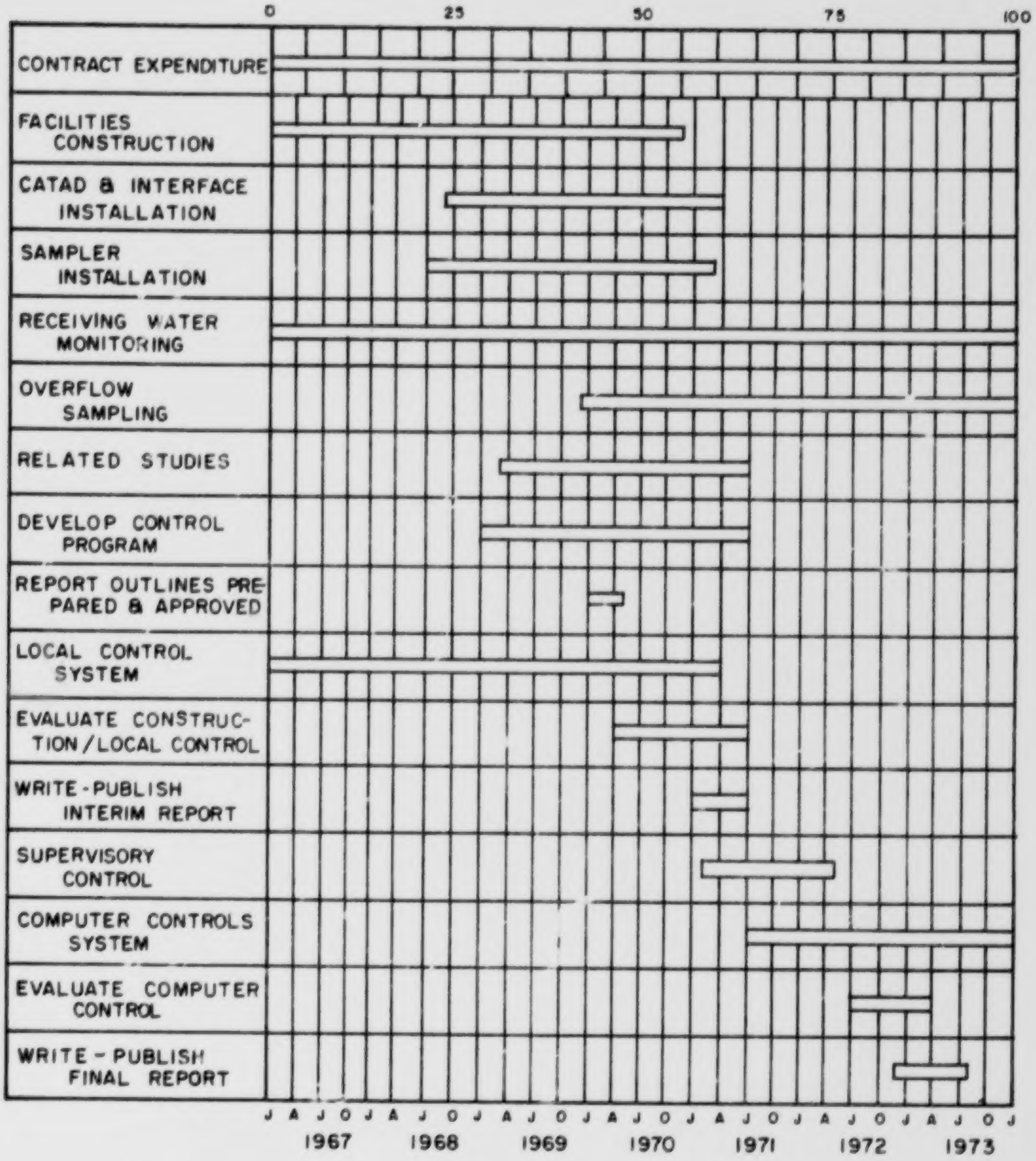


FIGURE 3

REVISED DEMONSTRATION GRANT
PLANNING AND PROGRESS CHART

Metro discovered the considerable staff effort required to manage and complete a demonstration grant of this magnitude and complexity. The first study requirement was a "Post Construction Studies Evaluation" report (14). This report was prepared by staff people normally assigned to other jobs. The preparation effort plus the additional work required to respond to questions of the federal awarding agency demonstrated the need to assign permanent responsibility for this project. A staff engineer was assigned coordination responsibility in September of 1967, and a regular reporting procedure on CATAD progress and construction form submittals was initiated. Construction plans were assembled and coordination of report production (Figure 4) was initiated. Regular monthly reports were submitted with special reports as conditions dictated. All reports associated with the production of this demonstration grant are referenced in this report or in the first project report (12).

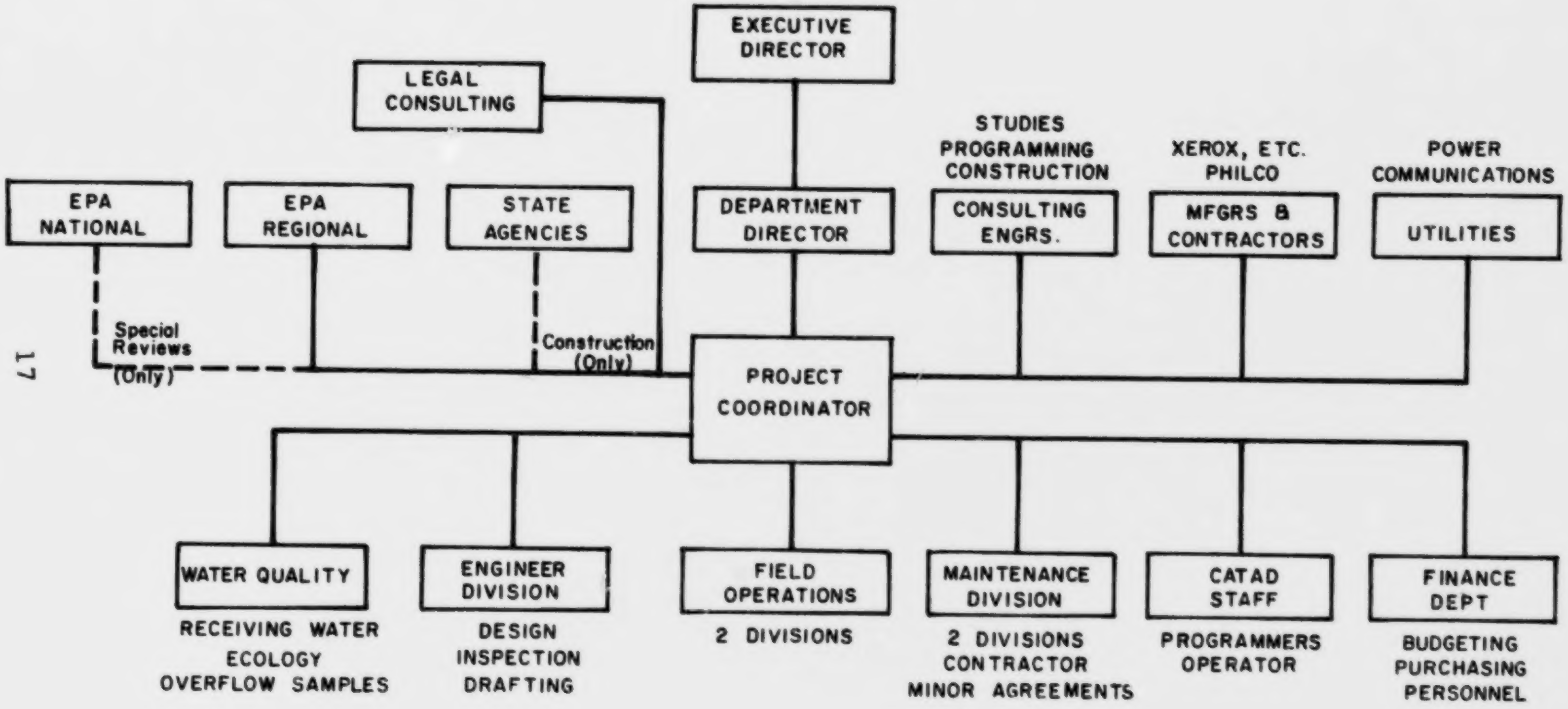

EXECUTIVE DIRECTOR
LEGAL CONSULTING
STUDIES
PROGRAMMING
CONSTRUCTION
XEROX, ETC.
PHILCO
POWER
COMMUNICATIONS
EPA NATIONAL
EPA REGIONAL
STATE AGENCIES
DEPARTMENT DIRECTOR
CONSULTING ENGRS.
MFGRS & CONTRACTORS
UTILITIES
Special Reviews (Only)
Construction (Only)
PROJECT COORDINATOR
WATER QUALITY
ENGINEER DIVISION
FIELD OPERATIONS
MAINTENANCE DIVISION
CATAD STAFF
FINANCE DEPT
RECEIVING WATER
ECOLOGY
OVERFLOW SAMPLES
DESIGN
INSPECTION
DRAFTING
2 DIVISIONS
2 DIVISIONS
CONTRACTOR
MINOR AGREEMENTS
PROGRAMMERS
OPERATOR
BUDGETING
PURCHASING
PERSONNEL

FIGURE 4

CATAD PROJECT COORDINATION NETWORK

CONSTRUCTION PROGRAM

The original grant request appropriated approximately 70 percent of the budget to construction with the remainder applied to the supervision, technical studies and services associated with the grant requirements. A brief overview of the construction work will simplify later explanations of control concepts. Section V provides a detailed explanation of the system hardware. Project construction work can be divided into three catagories:

1. Entirely new regulator structures built to develop storage within the system -- designed to allow remote control from the computer
2. Control modifications to existing remote stations that overlaid CATAD remote control on the existing pneumatic control systems
3. The central computer and supervisory control station itself -- the heart of the system.

Regulators

The CATAD concept maximizes utilization of in-system storage to reduce or eliminate overflows. A detailed description of the typical Metro dynamic regulator was presented in the initial report on this system (12). Several different regulator structure types were considered in programming as well as construction. Figure 5 shows regulator types from a typical diversion regulator to a storage-only regulator placed directly in interceptor lines. A list of regulators with hydraulic and cost data is presented in Appendix A. The first new regulator constructed was the Denny Way Regulator (Figure 5F). It is unique in that two separate trunk lines are controlled at this station. One trunk line has a large storage volume and is low in elevation, while the second trunk line has essentially no storage and a high elevation. If the two trunk lines were physically connected, storage in the larger Lake Union trunk would be lost. Separate controls at this location avoid this loss. The computer treats these two regulators as separate stations even though they are inside the same physical structure. Figure 6 shows interior and exterior photographs of this facility, which cost approximately $500,000.

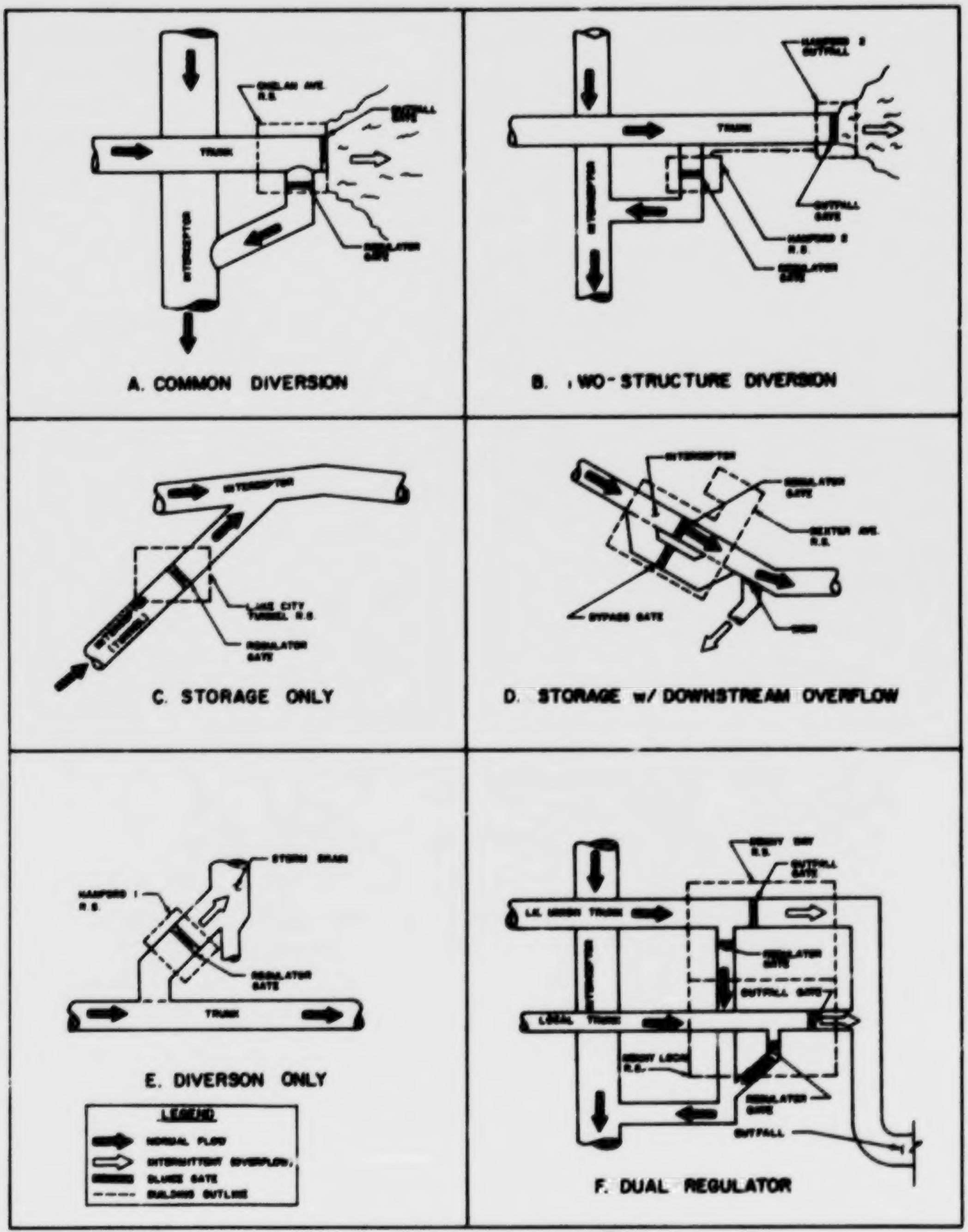

TRUNK
INTERCEPTOR
OUTFALL GATE
REGULATOR GATE
A. COMMON DIVERSION
TRUNK
INTERCEPTOR
OUTFALL GATE
REGULATOR GATE
B. ıWO-STRUCTURE DIVERSION
INTERCEPTOR
REGULATOR GATE
C. STORAGE ONLY
INTERCEPTOR
REGULATOR GATE
BYPASS GATE
D. STORAGE w/ DOWNSTREAM OVERFLOW
STORM DRAIN
REGULATOR GATE
TRUNK
E. DIVERSON ONLY
LEGEND
NORMAL FLOW
INTERMITTENT OVERFLOW
SLUICE GATE
BUILDING OUTLINE
OUTFALL GATE
REGULATOR GATE
OUTFALL GATE
LOCAL TRUNK
REGULATOR GATE
OUTFALL
F. DUAL REGULATOR

FIGURE 5

DYNAMIC REGULATOR TYPES

Reproduced from best available copy.

FIGURE 6

INTERIOR-EXTERIOR PHOTOS OF DENNY WAY R.S.

Within six months of the grant award, studies showed that storage locations within the collection system had been overlooked. Considerable interceptor storage was available in the Lake City tunnel. Metro requested that grant contingency funds be allocated to construct the Lake City tunnel regulator within the CATAD project. This facility is typical of in-line storage type regulators. Figure 7 shows views of this structure which cost approximately $150,000. The interesting, unexpected hydraulic problems presented by this installation should be reviewed by agencies contemplating this type of sluice gate regulator station. Construction of four additional sluice gate diversion type regulators was originally planned through demonstration grant funds. Some original budgeted costs were realigned; and these four stations along Elliott Bay were removed from demonstration grant budgets and funded from other sources.

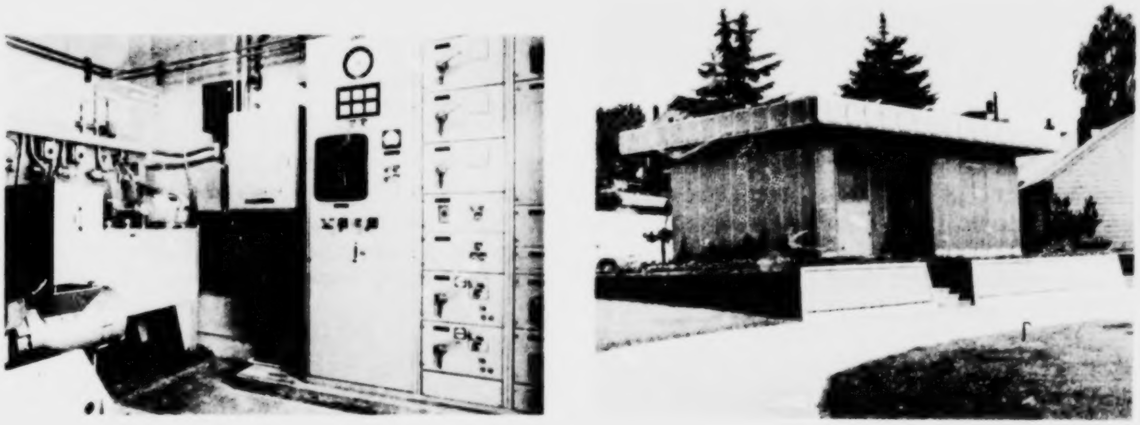


FIGURE 7

INTERIOR-EXTERIOR VIEWS OF LAKE CITY TUNNEL R.S.

Remote Station Control Modifications

When imposing centralized computer control on existing regulator stations and pumping stations, computer or telemetry failures originating in either hardware or software must not leave the remote station in a situation less desirable than existing proven controls. Alexander and Gibbs (15) described the original concept of superimposing computer control on an independent local control system while retaining reliable methods for reverting to local control in the event of computer system failures. Improvements to control hardware are described in this report (Section V). Briefly, regulator controls were converted to electrical instruments providing analog voltages to be converted and transmitted to the central computer. At the same time, an interface was provided to filter out expected remote station electrical transients.

The grant project's first construction contract was to supply electrical controls with remote sensors and transducers which would provide signals to the computer and would allow ramping type return to local control in the event of failure. Metro electricians and technicians installed this equipment because of their familiarity with station instrumentation and control philosophies.

The second contract provided cabinets and relay contacts plus other interface equipment. This interface contract also provided for a multi-conductor cable connection between the regulator and outfall gate control stations at two locations where these gates were 800 to 1000 feet apart. Coordination difficulties resulted from the large number of consultants, contractors and staff people involved in three or more simultaneous jobs, all trying to match up physically and electrically at some point on a drawing or map.

Experience gained in installation of these regulator station controls enabled engineers to combine all remote controls for the computer interface at each of eighteen pumping stations. Assigning the entire project, including supply and installation, to a single contractor provided better project control and an improved end product.

Computer Control Center

The last major construction was the computer control center. Foreknowledge of the time required to provide the computer and the programming might have segmented this project early in the demonstration grant so that control model programming could parallel hardware development. The computer contract called for a process control computer with peripheral equipment in an office building. A supervisory control console would display information from all remote stations. The contract required provision at each remote station of a control, coding and transmitting unit which would be the dividing line between computer equipment and Metro station equipment control and maintenance responsibilities. The contractor was to provide software (programming) which would demonstrate that the hardware could perform all basic functions required by the detailed operating specifications of the CATAD system (16). Other contractor provided features should also be considered by agencies contemplating such a control system. The contractor was required to train the agency staff people assigned to operate this system; and to provide a renewable annual maintenance function for the entire system.

A series of changes requested and implemented early in the progress of this contract have added immeasurably to the benefits and flexibility of the system. The prime contractor, Philco-Ford, within four months of the notification to proceed on the contract, suggested revision of the supervisory control, reducing the number of cathode ray tube displays and providing a separate console and wall map display similar to those in the NASA Houston Control center. Control push button arrays were suggested to permit flexibility in determining which stations and which commands would be utilized at various times in the life of the system. When Metro changed its timetable for future regulator construction, it became obvious that numerous telemetry control units would be idle for years, providing no information to the agency, while they deteriorated through disuse. The designated list of active terminal types was modified and telemetry unit allocation revised for installation in existing pumping stations as monitoring units. The map board and alarm displays were modified to improve the board's functional arrangement and appearance and allow a readily interpreted four-color segmented lamp display for each station without excessive board congestion. The map was enlarged to include future stations and extensions to the Metro system. Great flexibility allows future map revisions and changes to the system as construction is accomplished. Lesser changes to the CATAD computer room, both internal and external, are covered in other sections of this report.

Along with the station and control installation, the demonstration grant required considerable data accumulation for analysis of the success or failure of the system. Initial data collection equipment consisted of automatic sampling machinery installed at existing regulator stations. Samplers were triggered into operation by opening any outfall gate. Initially, a combination of sequential and composite type samplers was provided at seven stations. Improved versions of these samplers installed at other stations corrected deficiencies in the original design. A three-pen recorder was installed at the regulator structures to obtain overflow volume information from the regulator sites. The recorder plots water levels upstream and downstream of an outfall gate; and the outfall gate position. Standard orifice formulas allow calculation of flow through the outfall gate. Techniques for digitizing plotted information and converting it to flow data are described in this report based on three years experience with the sampling and recording equipment.

SECTION IV

DATA ACQUISITION REQUIREMENTS

GENERAL CONCEPT

This report intends to provide any agency considering implementation of a "total systems management" project with information to begin the accumulating and organizing requirements for data and equipment for the system. This section concentrates on the goals, objectives and data requirements which were an integral part of the development of the Metro Computer Augmented Treatment and Disposal system. A systems study of this magnitude not only generates information required to design the hardware to perform the desired functions, but it also pinpoints areas where information is lacking and suggests new types of sensors or additional manual studies which will provide the needed information.

The following paragraphs summarize the basic objectives and the concepts which provide guidelines for investigation of data requirements and system design.

The Municipality of Metropolitan Seattle, generally known as Metro, is a regional agency providing sewage collection treatment and disposal services to 11 cities and 23 local districts which provide sewer services directly to residential and business customers. Metro's "wholesaling" activities are performed by incorporating a large interceptor sewer system (Figure 8) which collects sewage flow from local trunk lines and then conveys this sewage to treatment plants. Interceptor sewer design capacity is based on the amount of sanitary sewage flow expected with ultimate planned development of the areas served. Most of Seattle is presently served by trunk or collector sewers carrying combined storm water and sanitary sewage. Metro's interception system cannot handle these combined flows. Peak sanitary sewage flow is only about 5 percent of the total flow in the trunk under storm flow conditions.

The flow of sewage into the interceptors from trunk sewers carrying combined flows is controlled by regulator stations which perform two functions:

1. Regulating the volume of flow diverted from trunk sewers into the interceptor sewer

2. Providing overflows into the Duwamish Estuary or into Elliott Bay for excess trunk sewer flows during storms.

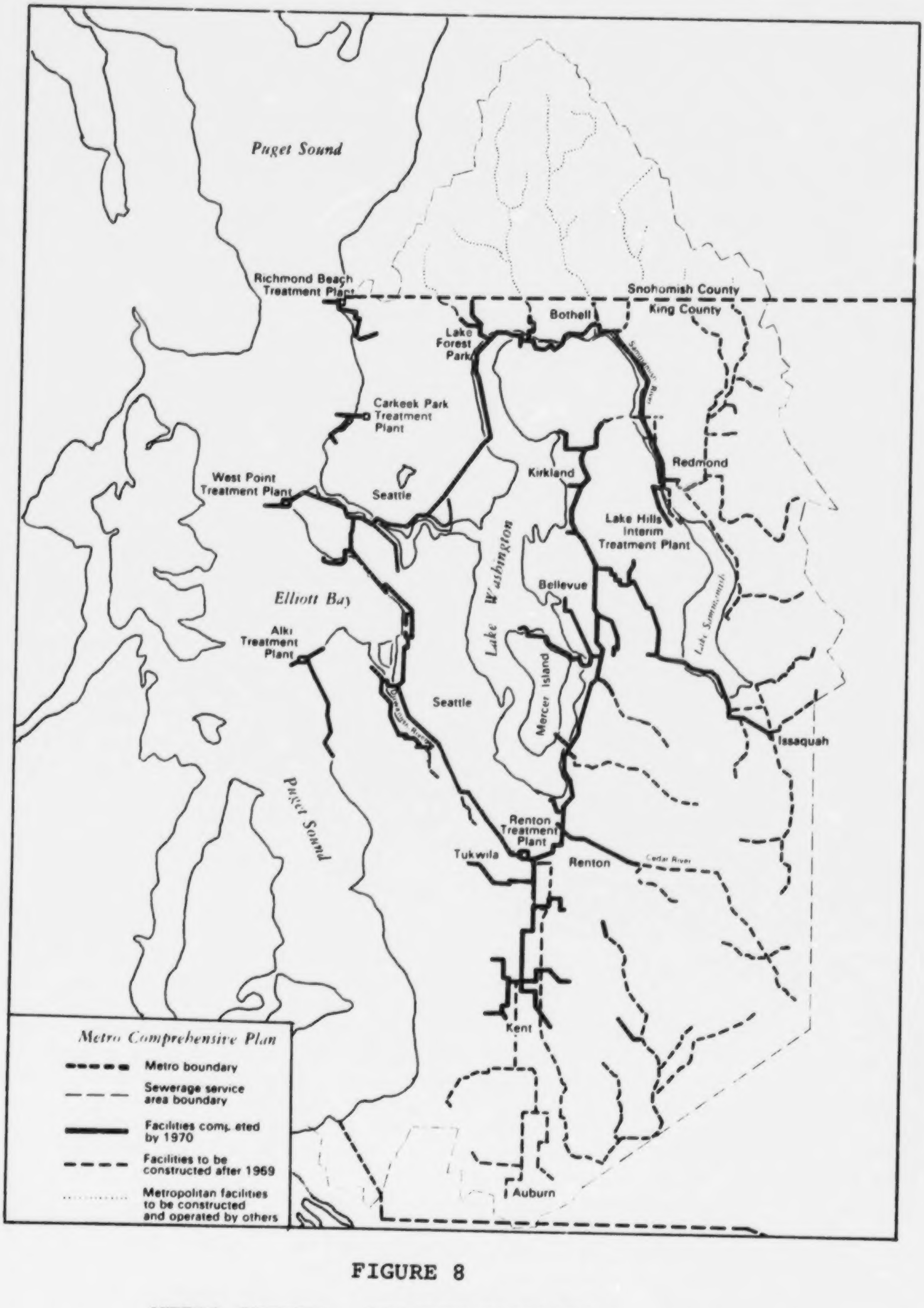

Puget Sound
Richmond Beach Treatment Plant
Snohomish County
King County
Bothell
Lake Forest Park
Carkeek Park Treatment Plant
Redmond
Kirkland
West Point Treatment Plant
Seattle
Lake Hills Interim Treatment Plant
Lake Washington
Elliott Bay
Bellevue
Lake Sammamish
Alki Treatment Plant
Mercer Island
Seattle
Issaquah
Puget Sound
Renton Treatment Plant
Tukwila
Renton
Cedar River
Kent
Auburn
Metro Comprehensive Plan
Metro boundary
Sewerage service area boundary
Facilities completed by 1970
Facilities to be constructed after 1969
Metropolitan facilities to be constructed and operated by others

FIGURE 8

METRO SYSTEM - PRIMARY FACILITIES

These unattended regulator stations operate under local station automatic pneumatic-electric type controls. Schematic diagrams of existing controls are presented and described in Section V.

Sewage flow from the trunk sewer through the diversion conduit into the interceptor is controlled by an adjustable regulator gate operated by automatic controls triggered by a preset maximum water level in the interceptor. Under normal conditions (no heavy storm water flows), the regulator gate is fully open and all trunk sewer flow is diverted to the interceptor. When the interceptor sewer level rises to the setpoint, the regulator gate closes in steps to maintain the preset level in the interceptor. When the trunk sewer flow exceeds the regulated flow into the interceptor, excess sewage is stored in the trunk until the level in the trunk reaches a preset point. An outfall gate then opens in steps to maintain the trunk level at the setpoint. Outfall conduits from some of the trunk sewers into the Duwamish Estuary are submerged by tidal variations of as much as 15 feet. In order to prevent saltwater or river water backflow into the trunk sewers, outfall gates at these stations have overriding controls which prevent outfall gates from opening when the tide is above the trunk level (16).

Note that the trunk setpoint is manually established at a regulator station so that at the worst possible combination of high tide, heavy storm flow in the trunk, and a fully laden interceptor line, the outfall gate opens soon enough to permit combined flow from the trunk line to escape from the sewer system through a fully opened outfall gate without flooding or backup conditions upstream in the trunk sewer drainage area. That setpoint remains essentially fixed through the various seasons unless manually altered. In the local control mode, each station is operated independently by instruments located within the station in response to signals from local sensing devices.

It would be difficult and time consuming to have persons visit each of the widely separated regulator sites to adjust the setpoints to compensate for dynamically changing water level conditions occurring during each storm. If it were possible to do this, setpoint adjustment could allow a higher water elevation to gain additional storage and reduce or prevent overflows. A centralized control facility utilizing a high speed computer makes these remote station adjustments in response to, or in advance of, variable storm patterns. The report "Maximizing Storage in Combined Sewer Systems" (12) describes storage within a combined sewer system under varying storm patterns using regulator gates and pump controls. Figures 9 and 10 show some nomenclature of these stations, the sensors which are monitored to generate information about storage, and the control signals which drive the machinery to achieve efficient use of that storage.

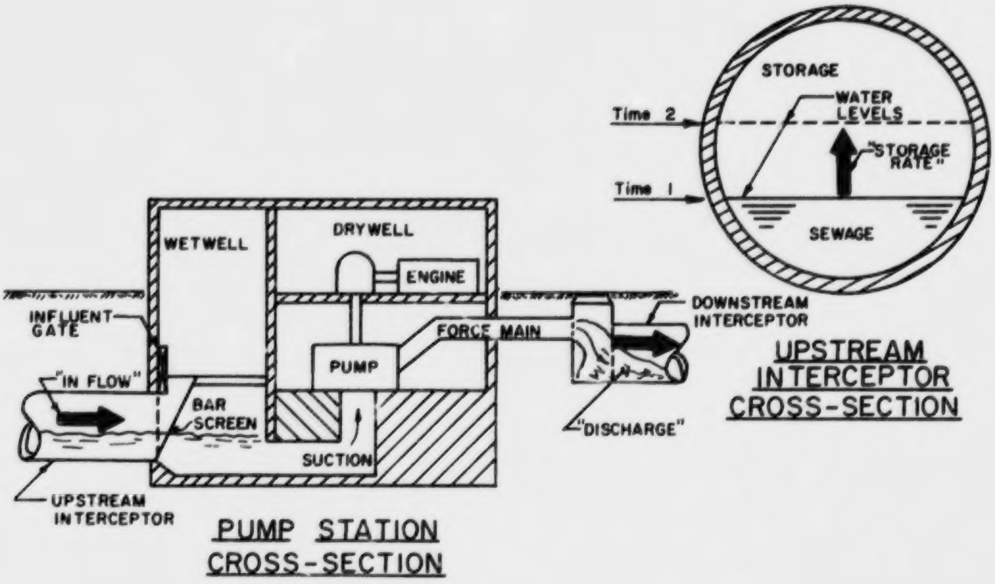

STORAGE
WATER LEVELS
Time 2
"STORAGE RATE"
Time 1
SEWAGE
WETWELL
DRYWELL
ENGINE
INFLUENT GATE
DOWNSTREAM INTERCEPTOR
FORCE MAIN
PUMP
"IN FLOW"
BAR SCREEN
SUCTION
"DISCHARGE"
UPSTREAM INTERCEPTOR
UPSTREAM INTERCEPTOR CROSS-SECTION
PUMP STATION CROSS-SECTION

FIGURE 9

FLOW COMPUTATIONS AT PUMPING STATIONS

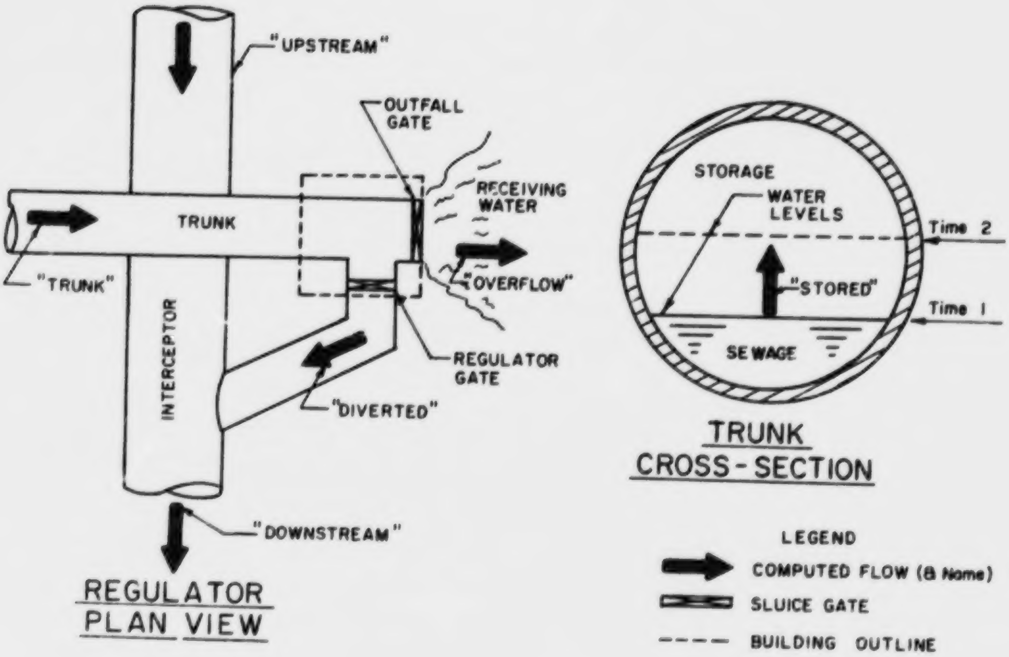

"UPSTREAM"
OUTFALL GATE
RECEIVING WATER
TRUNK
"TRUNK"
INTERCEPTOR
"OVERFLOW"
REGULATOR GATE
"DIVERTED"
"DOWNSTREAM"
REGULATOR PLAN VIEW
STORAGE
WATER LEVELS
Time 2
"STORED"
Time 1
SEWAGE
TRUNK CROSS-SECTION
LEGEND
COMPUTED FLOW (& Name)
SLUICE GATE
BUILDING OUTLINE

FIGURE 10

FLOW COMPUTATIONS AT REGULATOR STATIONS

The primary objectives of the Computer Augmented Treatment and Disposal system (CATAD) are:

1. To utilize the maximum storage capability of large combined sewer trunk lines and ultimate capacity of interceptor sewers to reduce or eliminate overflows caused by rain storms.

2. When overflows cannot be avoided because of storm intensity, the CATAD system selects the overflow points which will cause the least harmful effects on the receiving waters, beaches and marine life. Overflow decisions are based on water quality data monitored and stored within the computer. This information is regularly updated to reflect latest receiving water conditions.

3. Regulation of daily flows to treatment plants to aid in stabilization of treatment processes and effectively increase the dry weather capacity of existing treatment plants.

4. The CATAD system may eliminate or reduce cost of separating combined sewers which would be especially costly and disruptive to commercial/industrial areas and central business districts. Sewer separation may not have to be 100 percent, and/or it may be stretched over a longer period by optimizing use of the combined system as separation progresses.

If these objectives do not encourage a Municipality to embark upon "total systems management" concepts, proposed guidelines (17) regarding point sources such as combined sewer overflows or bypasses and stormwater outfalls will drastically increase the volume of data which will be required. Statements from the President's Council on Environmental Quality and EPA (18) and the General Accounting Office (19) outline the types and levels of control now proposed for these long ignored pollution sources. Sewer separation may compound the problem of urban waste collection and treatment since storm runoff may soon require some mandatory degree of treatment.

CONTROL STATION SELECTION

The design of a system which will carry out the objectives just described must establish whether all stations in the system will have both monitoring and control functions, or whether there will be some mixture of these functions within the collection system. Adding control functions to monitoring functions increases the remote facility cost by $3,000 to $6,000, depending upon controls necessary. For Metro's CATAD system, control instrumentation decisions were based primarily upon storage availability determined from a preliminary investigation of the system. This information is shown in Table 3 together with the final storage values determined by detailed studies and operating experience. Supervisory operation pinpointed connections into the system which had never been documented and which seriously affected the safe available storage in a trunk or interceptor line. Some of the greatest volumes of storage are available within interceptor lines such as the Lake City Tunnel and the Elliott Bay Interceptor upstream of Interbay Pumping Station. The largest trunk storage is available at the Hanford Regulator Station where approximately one million gallons of storage is available above the base average dry weather flow.

Cost factors affect command station decisions. The cost of controlling a multi-pump station with a very complex mode control arrangement may not be justified to gain a small amount of storage. It may be more economical to gain storage at some other site in the system or to consider installing permanent storage basins (20) underground or inflatable holding tanks (21, 22) for additional controlled storage. Engineering and economic factors must be weighed in deciding which stations will be command stations.

Metro system decisions resulted in the selection of the command stations shown in Table 3. The selection of these command stations did not preclude storage at other regulator stations in the system (not shown in Table 3). In fact, storage is generated at these stations by direct command of the regulator and outfall gates. Volume of storage is the main reason for calling a station a storage station.

For safety precautions, the special ramping type control system described in Section V was specified so that the large storage volumes would not create an overflow risk in case of computer or telemetry failures. Ramping controls gradually release a large volume of storage. At direct control stations, the volume of storage is considered too small to require this ramping procedure. In the event of computer or telemetry failure, any excess stored volume drains from the trunk to the interceptor without overflow risk.

Table 3. STORAGE AVAILABILITY IN COLLECTION SYSTEM

I. Trunk Storage

Station	Maximum Safe Storage (MG)		Average Dry-Weather Flow (MGD)		Maximum Storage Time (hours)[a]	
	Design	Actual	Design	Actual	Design	Actual
Eighth Avenue South	0.5	0.3	0.8	2.6	15.0	2.8
West Michigan Street	-	0.01	0.9	0.6	0.2	0.5
Chelan Avenue	0.4	0.4	3.0	2.2	3.2	4.4
Harbor Avenue	-	0.02	0.9	0.7		
Norfolk	0.4	0.2	5.8	2.7	0.5	0.6
Michigan	1.2	0.6	1.0	2.8	1.7	1.8
					28.8	5.14
Brandon	0.5	0.3	1.3	1.4	9.2	5.14
Hanford	3.8	3.2	4.6	5.1	19.9	15.1
Lander	1.4	0.7	1.5	3.7	22.4	4.5
Connecticut	0.8	0.3	1.6	2.2	12.0	3.3
King	0.1	0.3	2.0	2.0	1.2	3.6
Denny Way Lk. Union	0.8	0.6	2.5	6.9	7.7	5.8
Denny Way Local	-	0.4	3.0	4.1	0.5	2.3
Lake City Tunnel	6.5	2.8	10.0	6.8	15.8	9.9
II. Interceptor Storage Upstream from Pump Stations						
West Marginal	0.3	0.4	3.6	4.3	0.8	2.2
East Marginal	1.2	0.1	16.8	11.2	1.7	0.2
Interbay	9.3	5.8	35.0	48.0	6.4	2.9
Matthews Park	2.6	1.4	8.0	11.0	7.8	3.0

---

[a] For DWF only--Storage will reduce as average flow increases.

DATA COLLECTION REQUIREMENTS

Since the real-time computer deals with numbers, determining the types of data to be collected, measured, transmitted and stored in the form of numbers and characters (represented by digits) is extremely important in implementing a control system like CATAD. The agency must establish physical parameters to be monitored, forms of commands to be issued, and other data needs to get the system off the drawing boards, into specifications and under construction. Information requirements are:

1. Dynamic data includes the physical parameters monitored during each scan of remote stations; the command information sent to the station following the scan; and any other decision making processes in the program for supervisory control procedures.
2. Fixed data includes base information required to calculate elevations, flows, calibrations of instruments and maintenance factors; and
3. Strategy type information might initially be in tabular form to be used by a human operator in making control decisions. It might later be an equation or a computerized table used for automated command decisions.

The types, volumes and frequency of change or update of system information will have a great impact on selecting instruments and computer equipment to perform data gathering, analysis and storage.

DYNAMIC DATA NEEDS

The dynamic data requirements for the sewage collection system influence the selection of data communications equipment; the transmission line characteristics, and computer speed and capacity specifications. Water levels at many locations are probably the most important single category of information required to calculate flows and trigger certain types of alarms. By incorporating Manning's equations, various orifice and weir formulae and pump efficiency curves, it is possible to calculate flow at almost any location in the system. The computer checks water elevations with reference to overflow weirs to generate pre-alarms before overflows take place and/or actual alarms after the overflow has begun. Monitoring, control and modeling of the entire system depends upon flow information from many locations, some of which cannot be obtained from water level measurements alone. In the CATAD system, these additional on-line flow measuring techniques are employed:

1. Flow measuring weirs are installed at various locations

2. A calibrated propeller type flow meter is monitored at the West Point treatment plant site.

3. Force main pressure calibration methods are used at pump stations where there is sufficient friction head loss to calibrate force mains at various flow ranges.

Flow information and the water level data collected from these many locations throughout the system enable the programmer to calculate the amount of storage available in the various trunk lines and interceptors. Once this information is available, system storage can be monitored and controlled as described in Section VIII.

Once the primary transmission and receiving equipment has been installed, the data collection system can monitor equipment operating rates and status. An important pump station parameter is the pump rotational speed in revolutions per minute. This data is necessary in calculating flows using pump efficiency curves. At regulator stations, the most important information is gate travel. Since there are a variety of gates (some opening upwards and others opening downwards, and each gate has a different cross sectional appearance), it was decided to report gate positions as a "percentage open" figure. For stations with indirect, overriding control systems (15), it was necessary to provide "state-of-the-art" controls incorporating pulse counter devices. These pulse counters are monitored at all times so that a perfect change-over from remote control to local control is assured in any event.

The risks of encountering explosive atmospheres in combined sewers either through biological generation of methane gas or spills of explosive type fuels or cleaning agents, require an atmosphere monitoring system. Explosion hazard monitoring units were incorporated at various prime locations in the system to detect potentially hazardous conditions and to aid in the monitoring and investigation of some illegal hazardous material dumps into the collection system

A list of data monitored and definitions is summarized in Appendix B. Up to this point, the dynamic data refers to analog signal monitoring. Stations within the system range from four to eight active analog signals per station with an average of five and a maximum of twelve analog signals possible. A digital totalizer, which is driven by the pulse generator, advances and can be scanned to determine the number of pulses in a timed interval.

The status of equipment and different alarms at the remote station is monitored quite easily by providing relay contacts connected to various alarm sensors and status indicators. In all cases, a relay contact was interposed to prevent excessive voltages from entering the solid state electronic monitoring devices installed at each remote station. Examples of contact status information include:

1. A float switch monitor for high water levels
2. A "power on" indication
3. Air pressure sensor which indicates loss of instrument pressure
4. A status indication that a gate is moving either up or down.

These alarms will be discussed in detail in other chapters. For a list of contact status reported, refer to Appendix B. The number of status and alarm contacts scanned ranges from 10 to 48 monitored contacts per station with an average of 21 and a maximum of 64 possible.

Command procedures require additional dynamic data reporting to the central computer. In general, the computer command involves closing a hardware contact in a remote station followed by a physical movement of an instrument setpoint or gate position. The commanding logic continuously scans these contacts and equipment positions to assure that the command has gone to completion. Command output contacts range from zero to six per station with an average of four and a maximum of twelve possible.

System programs perform a three step command check. The contact closure is scanned to assure command initiation; secondly, the rate of movement of the setpoint or gate is checked at varying intervals to insure movement at a proper rate; and lastly, a test determines command action completion. The commanding procedures and various checks which comprise the dynamic data requirements for this function are reported in detail in Section VII of this report.

Before instrument selection and design, the engineer must know what degree of precision is desired and how frequently collection system information and commanding activities must be reported. Sewage collection and treatment precision is not quite as critical as in manufacturing processes; however, it cannot be ignored. Metro decided on instrumentation with a two to five percent precision and on remote station scanning at a minimum frequency of one minute, adjustable in four steps to ten minutes for dry weather conditions when system parameters are more stable. To achieve desired overall system precision, individual instruments in the system had to have precision on the order of 0.1 to 1 percent to compensate for the error multiplying effect from source to output.

During 1969 a series of weather analyses investigated those meteorological quantities which would provide the best information for predicting storm intensities and actual wet weather flows in the combined sewer system. Theoretically, a lead time in excess of two hours permitted excess storage being used for leveling dry weather flows to the treatment plants to be quickly released and the system drawn down as far as possible to gain the maximum amount of storage in preparation for the predicted rainfall. The results of the study were reported in reference (12). The correlations indicated that some combinations of barometer, anemometer, and wind direction could give predictive capabilities in excess of two hours. Since there is no advantage in competing with the weather bureau in predicting rainfall events, the four hour prediction reports issued by the weather bureau along with "chance of rain" indications are entered into the program logic by operators in deciding what levels of storage to maintain. Dynamic meteorological data requirements are limited to rain gaging stations at critical sites in the Seattle area.

Tipping bucket type rain gages are utilized. Each 0.01 inch of rainfall triggers an electrical pulse which is counted and stored at the remote station. The computer checks the rain gage totalizer during each scan to observe accumulated rainfall amounts and average rainfall rates. Six rain gages were installed initially. Further studies indicated that more rain gages were needed. Since the City of Seattle's manually operated system contained seventeen gages, Metro planned a minimum number of gages, assuming that serious gaps in the rain gaging system could be avoided by relocation or telemetering City gage data into the Metro system. This will provide detailed coverage in various drainage basins as required after flow and hydrograph predictions in the mathematical model routines are tested. Present rain gage locations are shown in Figure 11.

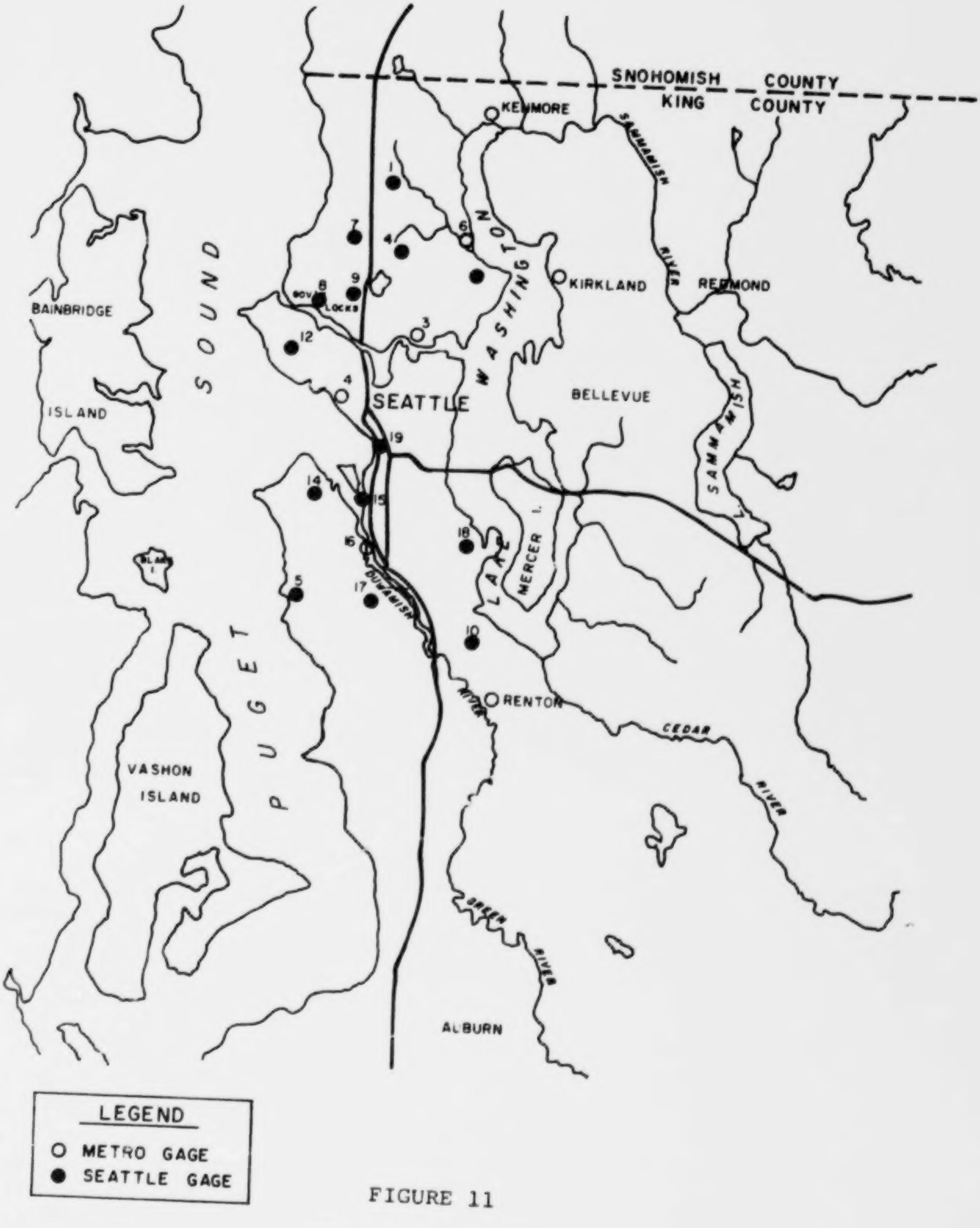

SNOHOMISH COUNTY
KING COUNTY
KENMORE
SAMMAMISH RIVER
REDMOND
KIRKLAND
LAKE WASHINGTON
BELLEVUE
LAKE SAMMAMISH
SEATTLE
PUGET SOUND
BAINBRIDGE ISLAND
VASHON ISLAND
BLAKE I.
GOV'T LOCKS
MERCER I.
DUWAMISH RIVER
RENTON
CEDAR RIVER
GREEN RIVER
AUBURN
1
3
4
4
5
6
7
8
9
10
12
14
15
16
17
18
19
LEGEND
○ METRO GAGE
● SEATTLE GAGE

FIGURE 11

RAIN GAGING SITES

Water quality data is important, primarily from the Duwamish River south of Seattle. If the river has oxygen deficit conditions at certain locations, these sites are considered critical areas and nearby overflow points are assigned a very low overflow priority. The computer or supervising operator selects the alternative available. The hourly data was to include temperature, dissolved oxygen, conductivity, pH, and turbidity at four river locations in the combined sewer area. River flow in cubic feet per second was considered for water quality monitoring purposes. The combination of the water quality monitors and river quality information from a United States Geological Survey (USGS) gaging site some 20 miles upstream could provide sufficient model input data to predict the effects of overflows on the receiving water and thus aid in the selection or rejection of overflow sites when alternatives were available. The idea was rejected because of the complexity of modeling a tidal estuary and because USGS was working on such a model. A cooperative effort whereby Metro collected data and USGS worked on the model was initiated in 1964.

In addition to the base elevation data for remote stations, basic information is needed about equipment speeds and limits as well as pump efficiency curves and existing control schemes. The computer can then compare rates, speeds and other control data with fixed information stored on disk files for rapid access and comparisons. Fixed data collection for the Seattle collection system and station equipment was aided by the relative youth of the system. Except for the trunk sewers, most of the system was less than ten years old when the information was compiled. Fixed data accumulation may be difficult for municipalities considering such a system if their files have not been kept up to date with all changes since original installation.

Lastly, drainage basin size and runoff characteristics are necessary to enable the computer to generate or select an inflow hydrograph due to rainfall from a particular storm. For the CATAD system, approximately forty drainage basins within areas tributary to the Elliott Bay and Duwamish interceptors were analyzed.

STRATEGY DATA

A fourth major category of system data which effects selection of instruments and computer hardware to satisfy all requirements is called "Strategy Information". This data is filed for ready access and provides either a human operator or the computer modeling logic with restrictions and control strategies which allow optimum overall system control decisions. In a supervisory control mode where human operators must make decisions, they must have available at a moment's notice such information as "safe" storage volumes or water levels and limits on the speed of movement where this type of information might be of considerable importance. Pump changes performed too quickly may result in a dangerous and potentially damaging pump cavitation. The CATAD system provides the operator with a detailed summary of local control instrument setpoints so that changes from one control mode to another are based on actual dynamic data which predict the consequences of switching from remote to local control.

For automatic operation, a controlling logic termed a "rule curve" as described by Alexander (24) was chosen as the basis for control strategy. Rule curves were designed and stored for each control location in the system and for each type of storm situation considered. Rule curves are discussed in Section VII. For municipalities considering some other form of control logic, rule curve data would not be required, but some form of command strategy information would have to be retained for each commanding situation.

Another factor which influences the selection of computer equipment for the control system is the amount and duration of data retention -- which items are to be saved and how they will be stored. Data retention media include anything from an hourly log on paper forms to a dense magnetic tape or disk storage. Data storage decisions can be combined with previous decisions regarding dynamic, fixed and strategic data collection requirements to develop specifications for the system. The next section describes Seattle Metro CATAD system selection and assembly based on the data requirements decisions made in the early phases of this demonstration grant.

SECTION V

PROJECT CONSTRUCTION

GENERAL

Approximately 68 percent of the cost of the CATAD project was expended for equipment or facility construction and modification which, for the purposes of this report, are categorized inclusively as construction. System hardware refers to the equipment which, after installation, allowed a computer based central monitoring and control capability. Project construction included two regulator stations and control modifications to all remote stations to complete the communication and control links which are discussed in detail in this section.

CATAD SYSTEM HARDWARE

The principal hardware items included in the CATAD System controls are as follows:

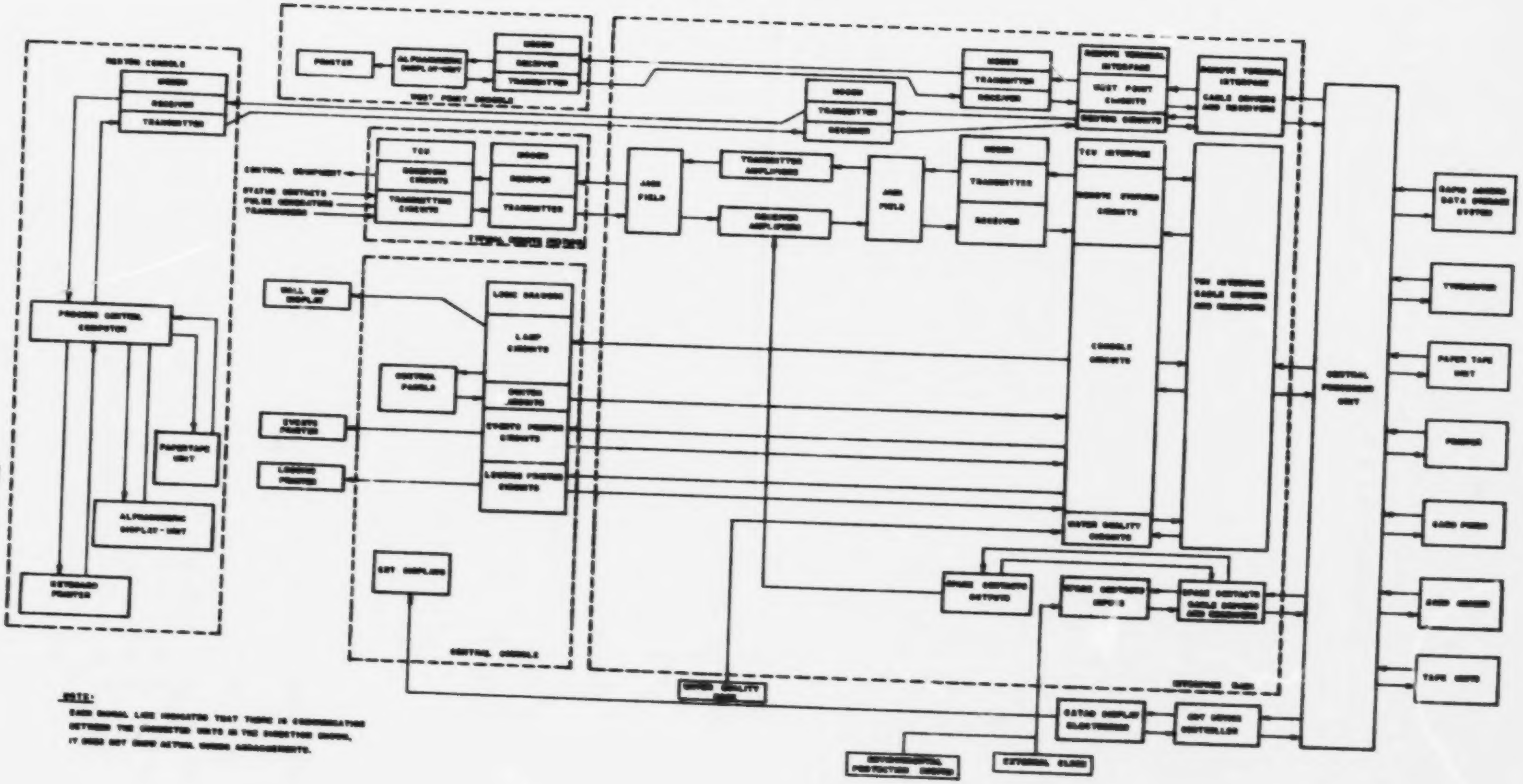
1. Central Computer
2. Secondary Storage
3. Peripheral Equipment
4. Central Control Facility
5. Telemetry System
6. Satellite Control Terminals
7. Water Quality Monitor Interface

A system block diagram is shown in Figure 12.

CENTRAL COMPUTER

Central Processor

CATAD System operation is directed by a general-purpose computer provided with special hardware features for real-time applications; including hardware interrupts, a real-time clock and power fail safe (see Table 4).


MODEM
RECEIVER
TRANSMITTER
PRINTER
ALPHANUMERIC DISPLAY UNIT
WEST POINT CONSOLE
TCU
RECEIVING CIRCUITS
TRANSMITTING CIRCUITS
CONTROL EQUIPMENT
STATUS CONTACTS
PULSE GENERATORS
TRANSDUCERS
TYPICAL REMOTE STATIONS
PROCESS CONTROL COMPUTER
PAPERTAPE UNIT
ALPHANUMERIC DISPLAY UNIT
KEYBOARD PRINTER
WALL MAP DISPLAY
LOGIC DRAWERS
LAMP CIRCUITS
CONTROL PANELS
SWITCH INPUTS
EVENTS PRINTER
EVENTS PRINTER CIRCUITS
LOGGING PRINTER
LOGGING PRINTER CIRCUITS
CRT DISPLAYS
CENTRAL CONSOLE
TRANSMITTER AMPLIFIERS
RECEIVER AMPLIFIERS
REMOTE TERMINAL INTERFACE
WEST POINT CIRCUITS
REMOTE TERMINAL INTERFACE CABLE DRIVERS AND RECEIVERS
TCU INTERFACE
REMOTE STATIONS CIRCUITS
CONSOLE CIRCUITS
WATER QUALITY CIRCUITS
TCU INTERFACE CABLE DRIVERS AND RECEIVERS
SPACE CONTACTS OUTPUTS
SPACE CONTACTS INPUTS
SPACE CONTACTS CABLE DRIVERS AND RECEIVERS
CATAD DISPLAY ELECTRONICS
CRT DRIVER CONTROLLER
EXTERNAL CLOCK
CENTRAL PROCESSING UNIT
RAPID ACCESS DATA STORAGE SYSTEM
TYPEWRITER
PAPER TAPE UNIT
PRINTER
CARD PUNCH
CARD READER
TAPE UNITS

NOTE:
EACH SIGNAL LINE INDICATES THAT THERE IS COMMUNICATION BETWEEN THE CONNECTED UNITS IN THE DIRECTION SHOWN. IT DOES NOT SHOW ACTUAL WIRING ARRANGEMENTS.

FIGURE 12

BLOCK DIAGRAM - CATAD HARDWARE

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Table 4. COMPUTER SYSTEM EQUIPMENT

Name	Manufacturer	Model Number
Computer System	Xerox	Sigma 2
Central Processing Unit (CPU)	Xerox	8001
Real-time clocks (4)		
Power-fail interrupts		
Memory protect feature		
Parity error interrupt		
External interrupts		
Multiply/divide hardware		
External core memory		
Direct I/O system		
Buffered I/O channels (12)		
Watchdog timer		
Rapid Access Disk (RAD) Storage System	Xerox	7204
Magnetic Tape Units	Daconics (Hewlitt-Packard)	2914
Keyboard Printer	Xerox (Teletype)	8091(KSR35)
Buffered Line Printer	Xerox	7440
Paper Tape Input/Output System	Xerox	7060
Card Punch	Xerox	7160
Card Reader	Xerox	7122
Plotter	Calcomp	563

The central processor provides 8 high-speed general registers, two of which may be used as index registers, 24 input/output registers and 16 memory protection system registers.

Main Memory

The basic storage unit is the 16-bit binary word. Main memory is magnetic core storage with a total cycle time of 900 nanoseconds. The system includes 49,152 words of core memory; 16,384 words of internal memory and 32,768 words of external memory. External memory may have independent data paths for external devices. Memory may be expanded to a maximum of 65,536 words.

The allocation of main storage among computer functions is shown on Table 5. About 50 percent of main storage is allocated to simple tasks which permanently reside in core storage. The other half is shared by tasks which reside in bulk storage and are loaded into main storage before execution.

Table 5. CENTRAL COMPUTER
MAIN STORAGE ALLOCATION

Function	Memory Allocation		
	Resident	Overlay	Total
Monitor System Resident	7,552	--	7,552
Monitor Extensions	1,376	512	1,888
Public Library	4,608	--	4,608
Common	6,912	--	6,912
Hardware Interrupt Handlers	1,056	--	1,056
Applications Programs	2,816	8,960	11,776
Background Batch Processing & Application Programs	--	12,288	12,288
Unassigned	--	3,072	3,072
TOTAL	24,320	24,832	49,152

The total storage required for applications programs is 24,064 words. However, 12,288 words are used only for a real-time system model which is executed at half-hour or one-hour intervals during storms and at two-hour to four-hour intervals or not at all during dry weather periods. This storage is available much of the time for background batch processing, including compiling and assembling new real-time tasks. Many of the subroutines most widely used by programs coded in Fortran are in the public library for use in both real-time and background tasks, leaving a substantial amount of background storage for engineering studies.

Approximately 3,000 words of core storage are unassigned and available for additional real-time tasks pending completion of real-time programming. Unused core storage will be assigned to background tasks.

Instruction Set -- The instruction format provides 4 bits for the instruction operation code, resulting in a maximum of 16 unique instructions. Eleven operation codes are used for memory reference type, and five operation codes are used to develop instruction groups as follows: conditional branch instruction

(8); shift instructions (8); register-to-register instructions (15); direct control instructions (2); and input/output instructions (5). Optional hardware multiply and divide instructions are included in the memory reference instructions. Three basic addressing methods are available: relative, indirect and indexed; these may be combined. One level of indirect addressing is available.

Priority Interrupts -- A system of hardware interrupts is essential for a computer used for real-time control to permit asynchronous communications between the computer and external devices. A hardware interrupt signals the computer on the occurrence of an internal or external event and causes the computer program to transfer to a unique location in main memory after completion of the current instruction, unless inhibited (see below). After determining the cause of the interrupt, the computer may either begin a new task, if its priority is high, or defer the task and place it in a queue if its priority is lower than that of the task currently being executed.

Interrupts may be caused by internal hardware, such as a clock, by parity error circuitry, by memory protection circuitry, by program control or by external devices, such as console switches, teletypes, etc. A maximum of 146 hardware interrupts can be installed on the CATAD System computer, of which 34 have been furnished. A list of interrupts assignments is shown on Table 6.

Real-Time Clocks -- The central processor is provided with four real-time clocks. Each clock operates at a different frequency:

	Frequency hz	Interval Milliseconds
Clock 1	500	2
Clock 2	2000	0.5
Clock 3	60	16.7
Clock 4	8000	0.125

Each clock comprises a hardware counter which is incremented by the real-time clock at the clock frequency. When the counter increments to zero, the hardware automatically triggers a second counter = 0 hardware interrupt. Each counter consists of a dedicated core memory location which can be set under program control such that the counter = 0 interrupt may be triggered at

Table 6. INTERRUPT ASSIGNMENT

	Level
Internal Group	
Power On	1
Power Off	2
Counter #4	3
Counter #3 (60 Hz)	4
Counter #2 (2 KHz)	5
Counter #1 (500 Hz)	6
Parity Error	7
Protection Violation	8
Buffered input and output	9
Control panel (computer)	10
Counter #4 = 0	11
Counter #3 = 0	12
Counter #2 = 0	13
Counter #1 = 0	14
Watchdog timer	15
Telemetry (future)	16
Remote Station Telemetry	17
Water Quality Monitor	18
External Group 1	
Teletypes (Events and Logging)	19
Renton Satellite Terminal	20
West Point Satellite Terminal	21
Metro Executive (Applications Programs):	
Level 0 Commands	22
Level 1 Process alarm	23
Console Push Buttons	24
Executive (Applications Programs):	
Level 2 Digital Filtering	25
Level 3 Alarm Message	26
Level 4 CATAD Console	27
Level 5 Renton Terminal	28
Level 6 West Point Terminal	29
Level 7 Logging	30
Level 8 Flow Calculations	31
Level 9 System Model	32
Non-Resident Foreground	33
Monitor	34

any even multiple of the clock interval. A user interrupt handler routine at the counter = 0 interrupt resets the clock counter and initiates real-time tasks at programmed intervals.

Memory Protection -- Memory protection is required for a computer system used for concurrent processing of real-time control tasks and background batch processing. Memory protection is also required for testing and de-bugging real-time programs on-line. Because the CATAD system controls are developmental in nature, facilities for on-line debugging are necessary to permit various applications to be developed and placed on-line without interfering with programs previously developed.

Memory protection prevents a background task or an undebugged real-time task from either altering a location or transferring (branching) to a location outside of the area of core memory allocated for execution of the task. Memory protection may be implemented by programming, in which each instruction in a background task is checked for validity before execution; but such means increase processing time from 10:1 to 20:1 (or more). Such methods are not suitable for on-line debugging where program execution may be time-dependent. Hardware memory protection is therefore essential. Some machines protect program location against alteration but not against invalid transfer to these locations which can cause serious problems.

The memory protection feature on the CATAD system computer provides protection in "pages" of 256 words of main memory. The processor handles protected pages differently from unprotected pages in three ways:

1. Control may transfer from an instruction stored in an unprotected page to an instruction stored in a protected page only in response to an interrupt.

2. The contents of protected pages may be changed only by an instruction stored in a protected page.

3. An input/output (including internal control) instruction may be executed only if stored in a protected page.

Any violation of the protection status of a protected area will cause an interrupt to the central processor. The protection status of an area may be altered under program control of the computer.

Power Fail Safe -- Because the CATAD system will operate unattended most of the time, it must be able to resume operation after a momentary power interruption. Although the computer core memory is bistable (that is, it will not change state when power is turned on or off), the computer operating registers are volatile; and if power is cut off, they will be in a random state when power is restored. Therefore, a power interruption causes program error unless the status of the registers is restored when the power supply is restored.

Two means are appropriate for protecting real-time systems such as the CATAD system controls:

1. Providing a non-interruptable power supply; i.e., supply outside power to a battery charger which powers a static inverter with back-up batteries.

2. Providing automatic power-off/power-on facilities.

The first method is used for power system controls where the equipment must continue to operate through a power interruption to the computer. The second method is suitable for systems such as CATAD where a short interruption is acceptable.

The power supplies to the computer logic contain sufficient capacitance to continue computer operation for several hundred microseconds after power is cut off. Voltage level detectors interrupt the processor at separate priority levels for both low-voltage (power off) and return-to-normal-voltage (power on) conditions. These interrupts enable the monitor to direct an orderly storing of volatile register contents and of interrupt status as system power fails and to insure an orderly computer restart after peripherals have come back up to speed, thus maintaining system continuity through a power failure. An external battery-powered real-time clock can be read during the power-on and power-off sequences to determine the duration of the outage. The programmer can define the length of power outage permitted for restoration of the system to automatic control after power is resumed.

Input and Output Control

The computer provides two methods of input/output control:

1. A buffered input/output channel which operates under control of the input/output processor.

2. A direct input/output channel which operates under program control.

Buffered Input/Output Channel -- The buffered input/output channel is a high-speed channel having a maximum data transfer rate of 4000,000 bytes per second. Data transfers between core memory and external devices via the buffered I/O channel are under the control of the input/output processor. Data transfers, once initiated by the central processor, are carried out by the input/output processor independent of program execution by the CPU. The data transfers take place between clock cycles of the central processor (i.e., by cycle stealing), and the speed of the central processor is reduced accordingly. As the data transfer rate approaches the maximum transfer rate of the channel, the data processing speed approaches zero.

Each device communicating with the central processor through the buffered I/O channel is connected via a sub-channel controller. A maximum of 20 sub-channels may be connected to the buffered I/O channel, of which 12 have been provided on the CATAD systems. Sub-channel controllers may control a single device or multiple devices; however, multiple devices may be connected only to sub-channels 0 through 7. Sub-channel device assignments are shown on Table 7.

Table 7. INPUT/OUTPUT CHANNEL ASSIGNMENTS

Sub-channel Number	Device
0	Keyboard printer
1	Line printer
2	*Disk
3	Paper Tape
4	Card Punch
5	Card Reader
6	*Magnetic Tape (2)
7	Console CRT's
8	Spare
9	Spare
10	Plotter
11	Spare

The high-speed devices on the buffered I/O channel are the fixed-head disk and the magnetic tape units, with maximum transfer rates of 170 bytes per second and 38 bytes per second, respectively. Extensive disk transfers tend to slow down processing.

*Multi-device controller

Direct Input/Output Channel -- Data transfers on the direct input/output channel are made under program control. A single write instruction transfers a 16-bit word from a hardware register to a device specified by a 16-bit address. Similarly, a single read instruction transfers a 16-bit word from a device specified by a 16-bit address to a register in the computer. All inputs and outputs directly related to real-time control functions, except console CRT displays, are made via the direct input/output channel.

Watchdog Timer -- The watchdog timer detects system malfunctions resulting from a program hang-up or from failure of the system to respond to a command over the direct input/output channel. The watchdog timer is attached to the direct input/output channel of the computer and is provided with an interrupt to the central processor to signal channel malfunction. Program hang-ups are monitored by requiring a command to the watchdog timer at regular intervals. Failure to issue the command results in a contact closure, signalling a program malfunction. Program hang-up features of the Executive are described in Section V. In the CATAD system, the contact closure causes a relay to open, cutting off the telemetry to remote stations and placing the system in local control. A direct input/output channel malfunction is detected by monitoring the acknowledge signal from the channel. If the timer fails to receive an acknowledge signal within 64 microseconds, the timer simulates an acknowledge signal from the channel, so that the system does not hang up, causing an interrupt to the computer. The computer takes appropriate action as programmed.

SECONDARY STORAGE

Secondary CATAD system storage comprises a fixed-head disk drive and two magnetic tape drives (see Table 4). Both disk and tape drives are attached to the computer buffered input/output channel through multi-device controllers.

The disk has a capacity of 1.5 million words organized into 512 tracks. Each track is subdivided into 16 sectors of 180 words each. A separate read-write head is provided for each track, and the average latency time to the beginning of a random sector is 17 milliseconds (one-half revolution). Data transfer between main memory and the disk is at a rate of 170,000 bytes per second. Write-protect switches permit recording heads to be disabled in groups of thirty-two tracks, thus ensuring that the operating system, permanent data files and CATAD system control programs cannot be destroyed inadvertently. Under normal operating conditions, 160 tracks are write-protected.

Magnetic tapes are driven by direct-drive reel-and-capstan motors with tension arms and tape guides for feed and takeup. Transport rate is 37.5 inches per second. Data is recorded in a 9-channel format at a density of 800 bits per inch, resulting in an effective transfer rate of 30,000 bytes per second. The drives and the interface to the input/output controller were not furnished by the computer manufacturer; however, the interface is designed to permit the drives to be compatible with those of the manufacturer and to operate under control of the standard input and output routines.

PERIPHERAL EQUIPMENT

Peripheral devices for data processing input and output include a programmer's console, card punch, card reader and a line printer, a paper tape punch and reader, and a drum plotter. Manufacturer model numbers are listed on Table 4 while characteristics of the peripheral devices are summarized in the following paragraphs. Each device is connected to the buffered input/output channel through a single device controller.

Programmer's Console

The programmer's console is a Teletype KSR 35 modified by the computer manufacturer. Maximum printing speed is 10 characters per second. Most computer control commands are entered through the operator's console. All system hardware and program diagnostic messages are printed on the console.

Card Punch

The card punch punches in either of two modes, the binary or the Extended Binary Coded Decimal Interchange Code (EBCDIC). Cards are punched row by row at a rate of 300 cards per minute. An 8-bit EBCDIC character is translated automatically to its equivalent 12-bit card code. An automatic read after punch checks the punched data against input data. Two output stackers are provided to permit preselection of the stacker under program control.

Card Reader

A table-top photoelectric-type card reader reads cards in two modes, binary or automatic, at a rate of 400 cards per minute. Automatic read mode permits switching from EBCDIC to binary facilities and intermixing of EBCDIC and binary punched cards. A 1,200-card hopper and 1,000-card output stacker are provided.

Line Printer

The drum-type printer with 132 print positions prints from 628 to 800 lines per minute, depending on the characters being printed. The character set comprises 56 printable characters plus a blank. The printer controller includes a full line buffer to minimize tying up the input/output channel.

Paper Tape Input/Output

The paper tape input/output system comprises a paper tape punch and paper tape reader. The tape is in eight-channel format with no parity bit generation or checking. Any combination of eight punches is considered valid; therefore, all checking must be done by program in the computer.

Punch -- The punch operates at a maximum rate of 120 characters per second and is provided with takeup and supply reel mechanisms.

Reader -- The reader reads paper tape photoelectrically at a maximum rate of 300 characters per second.

Drum Plotter

The 30-inch incremental drum plotter operates at a speed of 300 steps per second with a 0.005-inch step size.

CENTRAL CONTROL FACILITY

The central control facility provides the means for communication between the CATAD system operator and the remote station data acquisition and control system. The principal features of the central control facilities shown in Figure 13 are an operator's console, map display board and logging and events printers. The operator can monitor data and command all operations at remote stations from the console. In typical operation, the CATAD system controls operate fully automatically. However, during the normal eight-hour work day while routine maintenance is in progress, the operator can check stations for proper operation, sensor calibration and status indication. The operator's console has been used extensively for testing hardware and programs during system development.

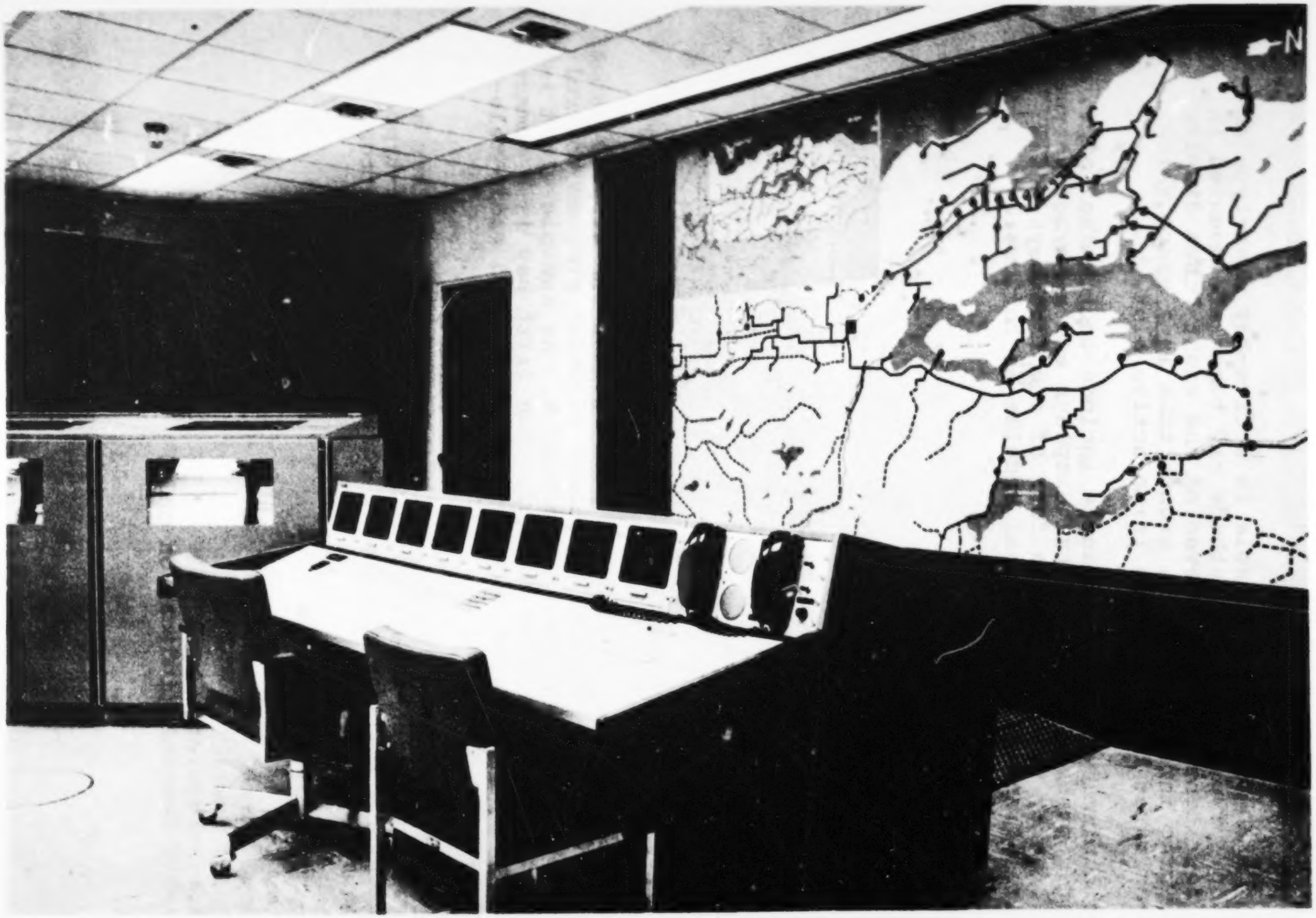

FIGURE 13

CATAD CENTRAL CONTROL FACILITY

Operator's Console

The CATAD operator's console is a five-bay desk-type configuration. Two eight-inch cathode ray tubes are mounted in each of four console bays. Seven of the eight tubes display alpha-numeric information; the eighth tube is a spare which can be activated by remounting in an active slot.

The control and display panels include indicating lamps, illuminated push buttons, digital displays and a keyboard-type numerical entry unit mounted in four of the five bays. The panels are arranged in functional modules as follows:

1. Digital entry module
2. Command module
3. Alarm and status module
4. Station select modules:

   West Point System
   Renton System
   Alki System

5. Segment select module

Operation of the illuminated push buttons and display lamps and the digital displays and keyboards is under program control of the computer as described in Section V. An audible alarm is also operated under program control. The fifth bay is a communications bay which includes a telephone handset and radio-telephone equipment.

Digital Entry Module -- The digital entry module comprises a four-digit projection-type digital display, a telephone-type push button keyboard and a group of illuminated push buttons labeled as follows:

Lamp Test (2)
Enter
Cancel Entry
Display Power
Alarm Acknowledge
Invalid Command (indication only)

Command Module -- The command module comprises a group of 21 illuminated push buttons which are the vehicle for entry of supervisory commands to remote stations, data entry and display control. Command module push buttons are shown in Figure 14.

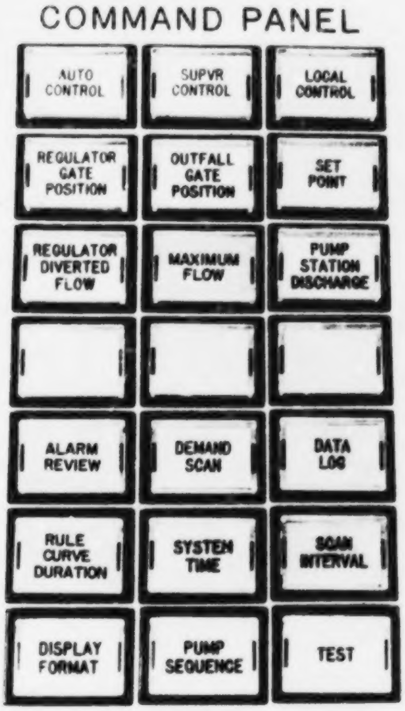
COMMAND PANEL
AUTO CONTROL
SUPVR CONTROL
LOCAL CONTROL
REGULATOR GATE POSITION
OUTFALL GATE POSITION
SET POINT
REGULATOR DIVERTED FLOW
MAXIMUM FLOW
PUMP STATION DISCHARGE
ALARM REVIEW
DEMAND SCAN
DATA LOG
RULE CURVE DURATION
SYSTEM TIME
SCAN INTERVAL
DISPLAY FORMAT
PUMP SEQUENCE
TEST

FIGURE 14

COMMAND MODULE PUSH BUTTONS

Alarm and Status Module -- The alarm and status module comprises a group of 42 indicating lamps on the operator's console. The lamps show the status at a selected station under program control. The function of each lamp is shown in Figure 15.

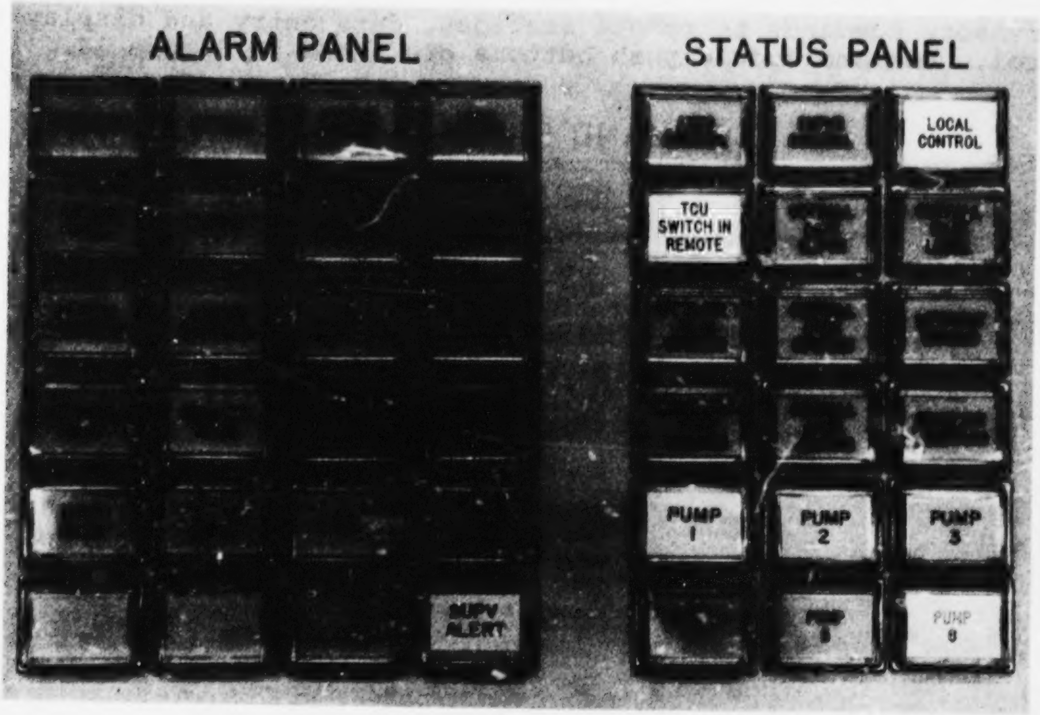
ALARM PANEL
STATUS PANEL
LOCAL CONTROL
TCU SWITCH IN REMOTE
PUMP 1
PUMP 2
PUMP 3
SUPV ALERT
PUMP 6

FIGURE 15

ALARM AND STATUS MODULE INDICATOR LAMPS

Station Select Modules -- The three station select modules comprise the following numbers of illuminated push buttons:

Module	Number
West Point Station Select	48
Renton Station Select	40
Alki Station Select	8

The station select push buttons control the alarm and status module display; sequence entry of supervisory commands to remote stations; and perform other display control functions (see Figure 16).

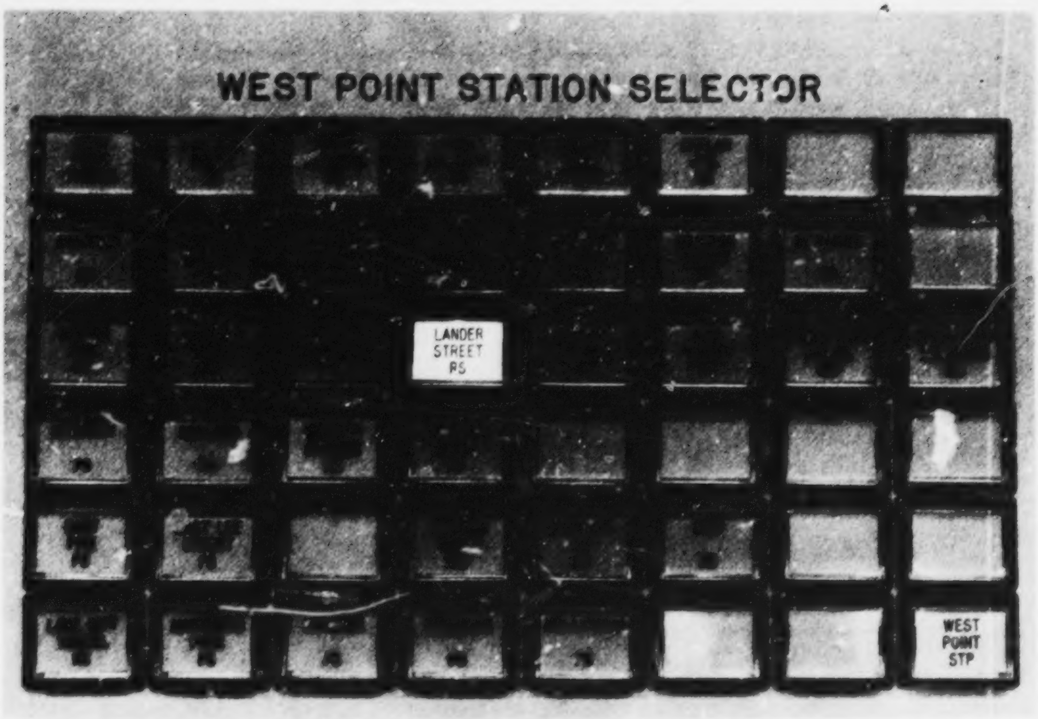

FIGURE 16

SELECTOR MODULE

Segment Select Module -- The segment select module comprises 20 two-segment indicating push buttons. The white upper half of each push button is illuminated when the segment is being displayed; the red lower half indicates the presence of an alarm condition at some station in the segment. The segment push buttons select the particular group of stations for which data is to be displayed on the console CRT's. The stations within each segment are logical groupings of related remote stations; e.g., stations along one continuous section of the interceptor, or stations in the vicinity of a major junction point or similar stations such as treatment plants (see Figure 17).

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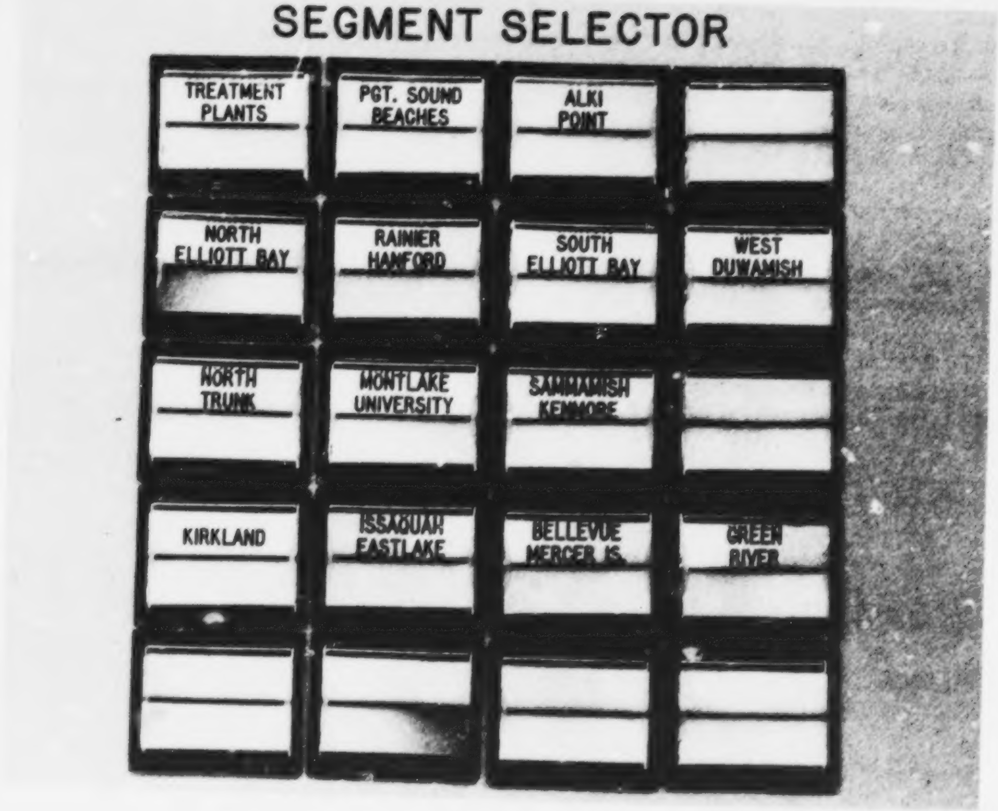

SEGMENT SELECTOR
TREATMENT PLANTS
PGT. SOUND BEACHES
ALKI POINT
NORTH ELLIOTT BAY
RAINIER HANFORD
SOUTH ELLIOTT BAY
WEST DUWAMISH
NORTH TRUNK
MONTLAKE UNIVERSITY
SAMMAMISH KENMORE
KIRKLAND
ISSAQUAH EASTLAKE
BELLEVUE MERCER IS.
GREEN RIVER

FIGURE 17

SEGMENT SELECTOR

CRT Displays -- CRT displays are eight-inch television monitors with a maximum display capacity of 24 rows of 32 characters per row for a total capacity of 768 characters. The displays are operated under computer program control which displays data at a group of stations determined by the segment select push button depressed by the operator. The operator may select one of three display formats via the command module:

1. Station hydraulic data
2. Station alarms
3. Station miscellaneous data

The operator may also designate any station as a "Test Station" for test and diagnostic purposes, causing a display of all analog data at the station in the form of voltages, with no conversion or scaling.

Map Display

The map display is a 12-foot by 7-foot graphic panel positioned behind the CATAD operator's console. Figure 18 shows a plan of existing, interim and future Metro facilities included within the CATAD system superimposed on an outline map of the area showing major bodies of water and major political boundaries. Each pumping station, regulator station and sewage treatment plant is designated by a graphic symbol. A four-segment, four-color indicating lamp is mounted within the symbols for existing or future CATAD stations. The indicating lamps are operated under computer program control. The design and interpretation of the segmented lamps is shown in Figure 19.

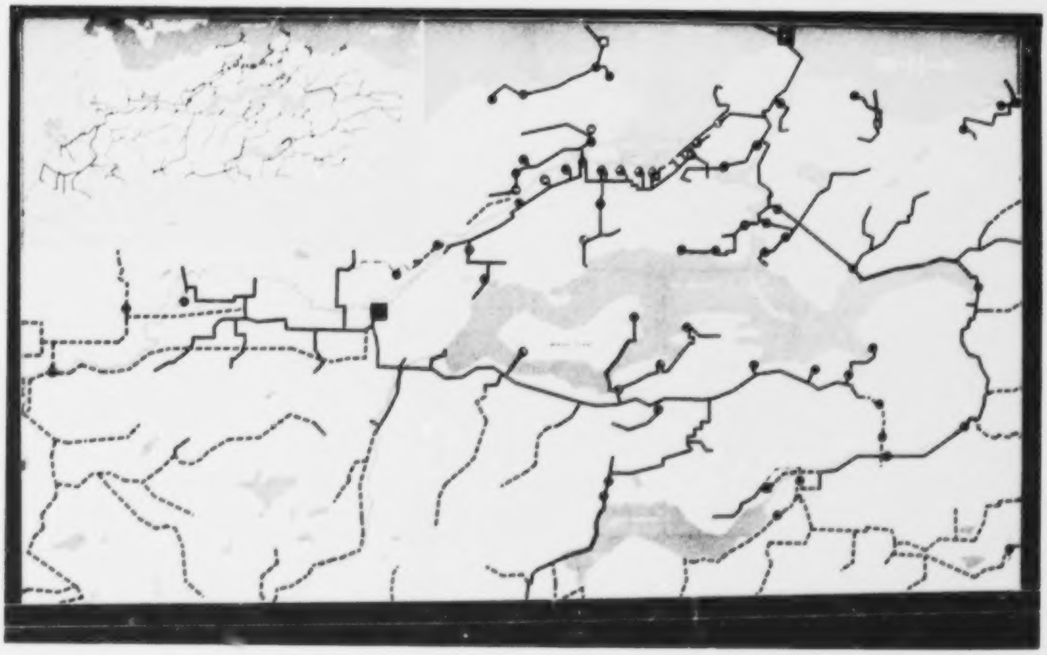


FIGURE 18

MAP DISPLAY

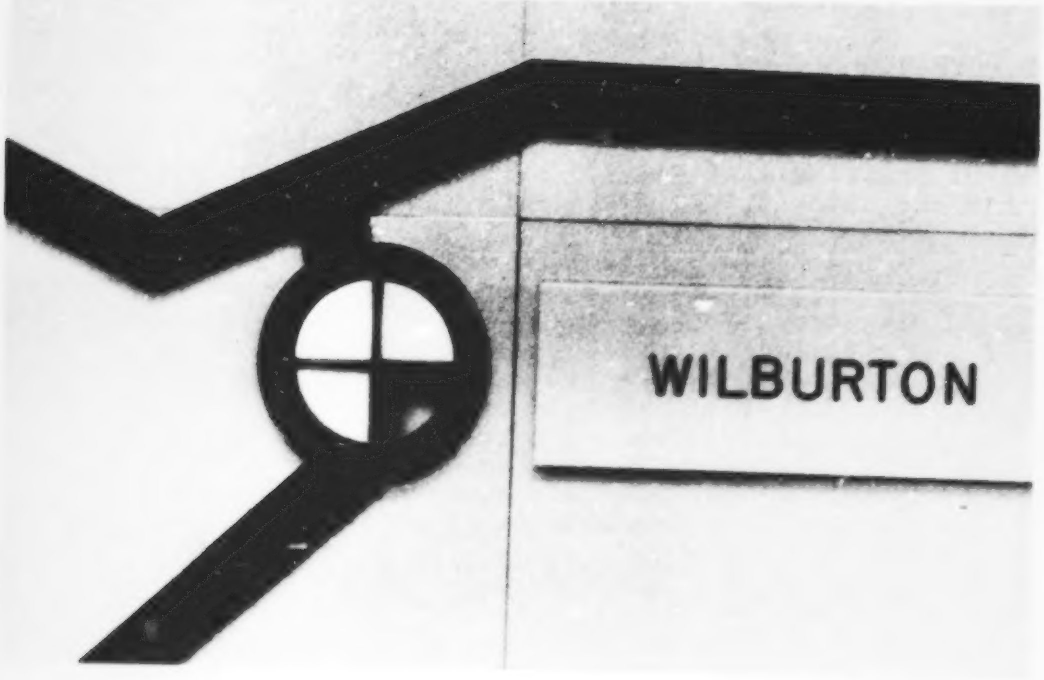


FIGURE 19

SEGMENTED LAMP CODES

Logging and Events Printers

Two printers adjacent to the operator's console print periodic data logs and record important operator actions and alarm messages. The printers operate at a speed of 15 characters per second on a 72-character line. The printers are controlled via the computer direct input/output channel using special-purpose interface logic located in the operator's console and interface rack.

Each character is output in ASCII code to either printer by a single direct output instruction. The least significant halfword (8-bit byte) received by the interface equipment is shifted serially to the printer after adding a start and stop bit. After the last serial bit has been received by the printer, an interrupt is transmitted to the computer to indicate that the transmission is completed and that the interface is ready for the next character.

Input and Output Control

Data transfers between the computer and the operator's console and map display are made principally via the computer direct input/output channel; however, output to CRT displays is made via the computer buffered input/output channel. Space contact inputs and outputs provide miscellaneous command and display functions at the central control facility. The electronic circuits for transferring data between the computer input/output system and the console, map board and printers, are located in logic drawers in the rear of the console and in racks located behind the map board.

Lamps -- Lamps on the console or map display are operated by the computer, which transmits two 16-bit data words to the lamp circuits via the direct input/output channel. Six bits of the first word designate the binary-coded address of one of 64 groups of 16 lamps. Each bit of the second word subsequently determines the state of a corresponding lamp in the selected group. After the second word is received from the computer, its data is strobed into the selected 16-bit lamp-driver register, which stores the state of the lamps for display. Thus, capability is provided for expansion to 1,024 lamps on the console and map board.

Switches -- Depressing a push button closes a switch, causing a interrupt to the computer, which initiates an interrupt-handler routine to determine which switch has been closed. Lamp and switch data transfers occur as word pairs via the input/output system. To input switch data, the interrupt-handler program responds to a switch-generated interrupt by reading two words of data which are generated simultaneously with the interrupt. The first word assembled by the switch data circuits has one bit set, representing one of 16 hard-wired groups of 16 switches. The second word indicates which switch in the selected group was pushed. Thus, capacity is provided for expansion to 256 console switches.

After the closed switch has been determined, the computer initiates a routine associated with the push button. The program turns console lamps on or off, causes the display, or initiates the control function associated with particular push buttons depressed by the operator in the prescribed sequence.

CRT Displays -- Alphanumeric data displayed on the console CRTs is output from the computer through the buffered input/output channel. The displays are controlled by a CRT device controller and by a CATAD display electronics unit. The controller handles communication with the computer channel while the display electronics unit stores, decodes and demultiplexes information to the several displays.

The CRT device controller contains a channel subcontroller which provides address recognition and connection to the computer's buffered I/O system. Information for display is received from the computer in blocks of eight-bit bytes under the direction of the device controller and is held in a twelve-byte buffer. The controller provides control, status, interrupts and other signals required by the system.

The display electronics unit contains equipment for all seven display channels and is expandable to include one more channel. Control circuitry writes received data into specified locations in the refresh memories which are separate, full-screen delay-line memories provided within the unit for each display channel. All channels time-share a common symbol generator which converts each memory byte into a seven-line alphanumeric character for display. Seven separate video amplifiers compose the final signals from information received from the symbol generator and synch generator circuits and drive the console-mounted monitor screens.

Spare Contact Inputs -- Spare contact inputs have been provided at the central facility for miscellaneous digital inputs to the computer via the direct input/output system. The contact inputs are arranged in 16 groups with 16 contact inputs in each group for a total of 256 spare contact inputs. Three of these groups are presently used for the following purposes:

1. Input of time from battery powered external real-time clock.

2. Input of status from environmental protection system for monitoring fire, smoke, etc.

Spare Contact Outputs -- Spare contact outputs at the central facilities provide miscellaneous computer control functions via the direct input/output channel. The contact outputs are arranged in 8 groups with 16 contact outputs in each group for a total of 128 spare contact outputs. One of these groups presently controls switching of the central station telemetry equipment on the various telephone circuits.

TELEMETRY SYSTEM

The telemetry system provides communication between the central control facility and remote stations for data acquisition by the computer and issuance of control commands to the remote stations (see Figure 20). All data is transmitted serially in on-off digital bit form. A single telemetry interface unit at the central station communicates with all remote stations.

Telemetry Control Units

The remotely located telemetry control unit (TCU) provides interface between the CATAD System and the control equipment and sensors at each remote station. Thirty-seven TCU's were furnished under the CATAD System contract. Two TCU's are required for one of the regulator stations which regulates flows from two trunks; therefore, a total of 36 remote stations may be controlled using existing equipment. Each telemetry control unit is mounted in a 2' x 2.5' x 1.5' sealed enclosure with a locking door. A lamp display on the door permits maintenance personnel to read the on-off condition of each contact and the pulse rate of each pulse input.

Original plans called for installing the equipment in the West Point and Alki Systems. A future telemetry system was planned to monitor and control the Renton System from the existing central computer. As a result of construction delays in the West Point and Alki Systems, nine TCU's have been temporarily installed at key stations in the Renton System to evaluate the benefits of central control of this facility.

Data Acquisition

The data acquisition system within the telemetry control unit at each remote station provides facilities for acquiring three types of data:

1. Contact status inputs
2. Analog inputs
3. Pulse count inputs

Contact Status Inputs -- Contact status inputs indicate operating status and high or low alarm limits. Digital inputs are summarized on Table 8. A minimum of 40 and a maximum of 65 contact inputs are available at the TCU.

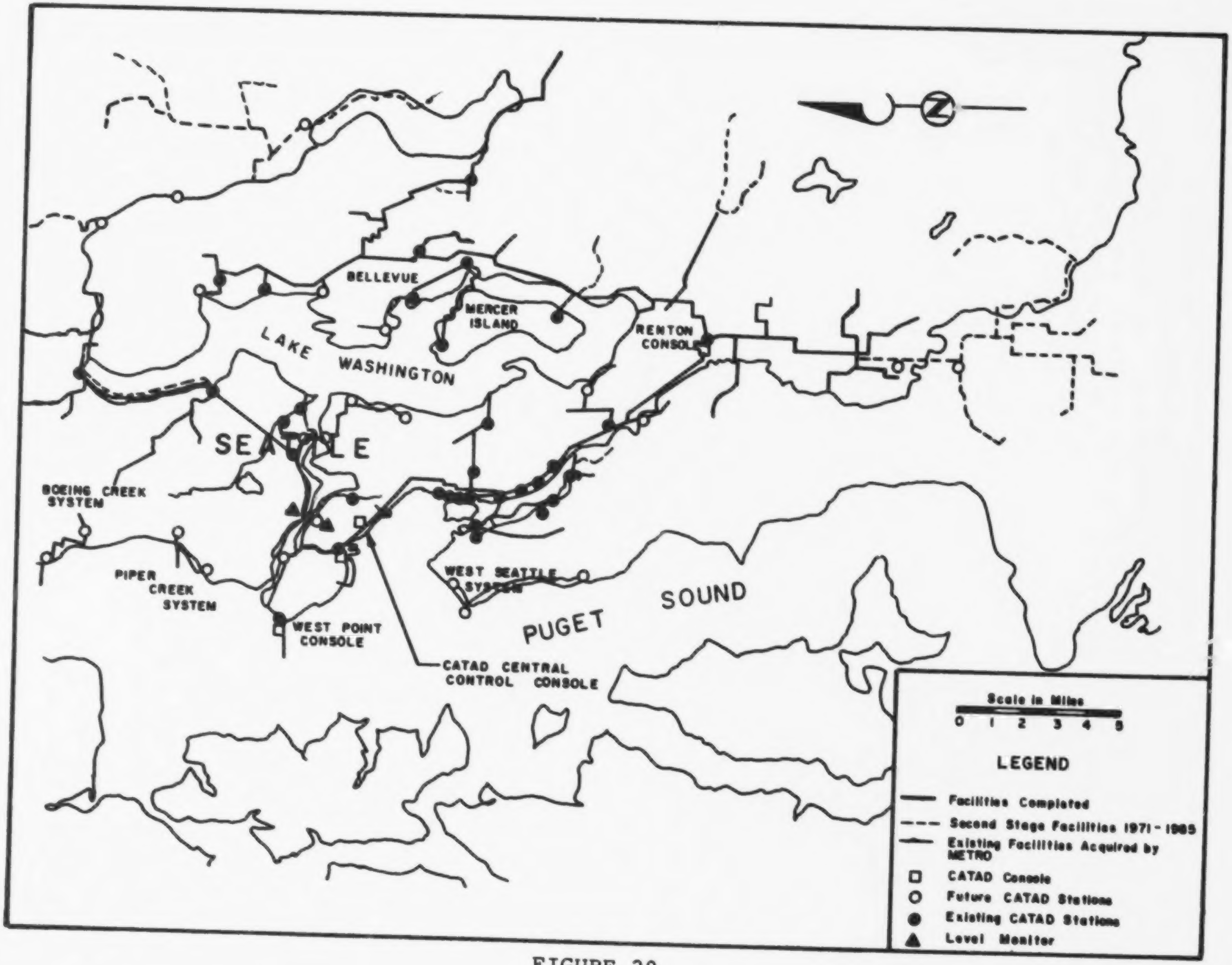

LAKE WASHINGTON
BELLEVUE
MERCER ISLAND
RENTON CONSOLE
SEATTLE
BOEING CREEK SYSTEM
PIPER CREEK SYSTEM
WEST POINT CONSOLE
CATAD CENTRAL CONTROL CONSOLE
WEST SEATTLE SYSTEM
PUGET SOUND
N
Scale in Miles
0 1 2 3 4 5
LEGEND
Facilities Completed
Second Stage Facilities 1971 - 1985
Existing Facilities Acquired by METRO
□ CATAD Console
○ Future CATAD Stations
● Existing CATAD Stations
▲ Level Monitor

FIGURE 20

CATAD LOCATION MAP

Table 8. REMOTE STATION STATUS INPUTS

Pumping Stations	Regulator Stations
Pumping status (6)	Regulator open
Power monitor (4)	Regulator close
Instrument air	Regulator opening
Emergency generator	Regulator closing
Pumping unit (6)	Outfall gate open
Wet well level (2)	Outfall opening
Influent gate closed	Outfall closing
Starting air monitor	Outfall bypass open
Bar screen differential	Computer/local
Fluid power system (4)	Power monitor (3)
Explosion hazard	Instrument air (2)
Setpoint (2)	Selector switch auxiliary (2)
Remote/local (2)	Emergency generator (2)
Water system monitor	Fluid power system
Flood hazard (2)	Explosion hazard (2)
Operating mode (12)	Trunk high level (2)
Telemetry failure	Setpoint (2)
Generator set (3)	Remote/local (2)
Pump discharge valve (12)	Computer lockout
Crossover valve (2)	Service air
	Equipment room flood
	System master control
	Telemetry failure

Analog Inputs -- Analog inputs are received from water-level, pump-speed and gate-position sensors. Signals from each type of sensor are input to an analog-to-digital converter as 2V to 10V variable signals. The analog-to-digital converter provides a 10-bit binary output at a maximum rate of 20,000 conversions per second. (Note: The conversion rate far exceeds the specification requirements, but is standard with the supplier.) Analog signals are multiplexed through a single A-D converter. The multiplexer converts each signal in turn and initiates data transmission to the central terminal. A maximum of 11 analog signals may be input to each TCU. In addition to process analog signals, a constant reference voltage input to the A-D converter at each station is read during each data scan to verify proper converter operation.

Pulse Count Inputs -- Pulse inputs are received from two sources:

1. Pulse generators used in control circuits at pump and regulator stations which operate under remote control.

2. Tipping-bucket type rain gages used to obtain rainfall measurements.

Pulses are collected in a nine-bit binary counter (512 counts). Up to four pulse counters may be installed in one TCU.

Control

All remote controls for the CATAD System are on-off contacts which energize or deenergize interposing relays. Each relay has a rating of 5 amps @ 120 VAC or 28 VDC and is provided with 2 form "C" contacts. Up to 12 contact outputs may be installed at each TCU, including 2 outputs which determine the station's control mode.

Message Format

A very high level of security is provided by the following procedures:

1. Each data or command message contains a parity bit.
2. Each message is transmitted twice and compared bit by bit.
3. The second transmission is complemented (inverted).

Each data or command message contains 10 bits of information. Three control bits are added to each message, including a parity bit, resulting in a 13-bit message. A single transmission comprises a 31-bit word made up of the 13-bit message, its 13-bit complement and a 5-bit Barker code for synchronizing. The Barker code is a 5-bit synchronizing code (11001) which is detected by the hardware to indicate the beginning of a message (see Figure 21).

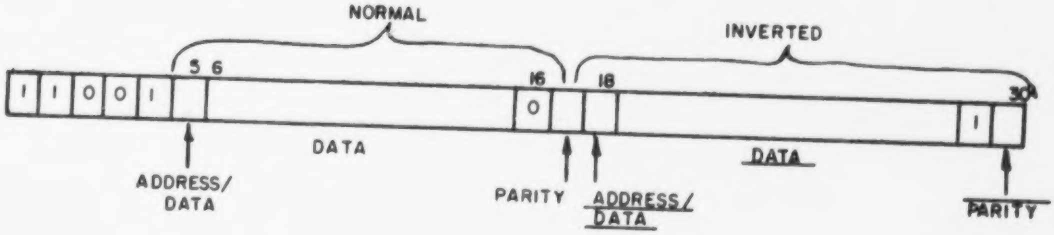


FIGURE 21

TELEMETRY MESSAGE WORD FORMAT

Message Transmission

All message transmissions to remote terminals are initiated by the computer under program control. The computer initiates all data scans and issues all commands to the remote station.

Commands -- Each command transmission to a remote station comprises three 31-bit words and includes 30 bits of information. The first word transmitted contains the station address. The remote station echoes the message back to the central station to acknowledge its ready-to-receive status. The second and third words each contain ten information bits indicating desired contact operate commands. Eight data bits in the third word are unused and ignored by the remote TCU, resulting in a total of 12 data bits used for commands.

At the remote station TCU, the Barker code is recognized, bits 6 through 18 are stored for comparison with bits 19 through 31, and parity is checked. If the ten information bits are recognized as a command addressed to the station, the 31-bit word is recomposed and returned to the central computer. If the next two words satisfy the redundancy and parity checks, the twelve information bits are strobed into a register controlling twelve relay drivers. Six relay drivers are in use at each regulator station, with four used at each pumping station. If the message does not satisfy the security checks, the commanded changes are ignored.

Data Acquisition -- Normal data acquisition is done by polling. At programmed intervals, the computer addresses a remote terminal, receives all data from that station and repeats the procedure in sequence for all remote stations. During control operation, the computer may address the station at which the control operation is in progress. During a poll, the computer addresses the stations at about one-second intervals. A complete data poll takes approximately 37 seconds.

A station scan is initiated by an address word from the central station to the remote station and an echo back from the remote to central. The acknowledge word from the TCU is followed by 24 data words separated by circuitry in the TCU into 6 groups of 4 words each in the following sequence:

Group	Data
1	4 Contact status words
2	4 Pulse counter words
3	4 Contact status words
4	4 Analog data words
5	4 Analog data words
6	4 Analog data words

One bit in each status word entering the computer is used to indicate failure of the corresponding telemetered word to satisfy validity checks at the receiving end. The computer can use this bit to detect a transmission failure and reinitiate the scan.

Modems

Data transmission uses frequency-shift non-return-to-zero (NRZ) coding at a transmission rate of 1,200 bits per second. Modems are three-frequency type with a center frequency of 1,700 Hz shifting + 600 Hz from mark to space. A continuous 2300-Hz mark signal transmitted from the central terminal to all remote stations is monitored by carrier detection modules at the remote stations. Loss of carrier signal opens a relay at a remote station which transfers the remote station to local control operation.

Communications Channels

Communication between the central station and remote terminals employs leased telephone circuits. Circuits are four-wire multi-point unconditioned Type 3002 circuits and comprise two simplex unidirectional pairs. Up to eight remote stations are grouped on a single multipoint circuit using an eight-way bridge. A single modem at the central facility is switched between six multipoint telephone circuits under computer control through contact outputs.

SATELLITE CONTROL TERMINALS

Satellite terminals to the CATAD System are located at the West Point and Renton sewage treatment plants. Each terminal includes a cathode ray tube (CRT) terminal unit and a hard-copy printer. Operators at each plant may monitor the complete system and may enter display requests, specific items of data and specific commands as programmed. All CATAD System control monitoring outside the normal eight-hour workday when the central control facility is manned, is done at the satellite terminals.

The following functions are presently performed by the satellite terminals:

1. Display and recording of alarms.
2. Data display under operator control.

3. Commanding (changing control mode).

4. Data entry for control and for recording.

The West Point Satellite Terminal, which was procured under the main CATAD System control contract, operates under fixed wired logic control. The Renton Satellite Terminal, which was procured subsequent to the main contract, operates under minicomputer program control.

West Point Satellite Terminal

The West Point Satellite Terminal comprises a CRT input/output terminal and a teletype printer (see Figure 22). The

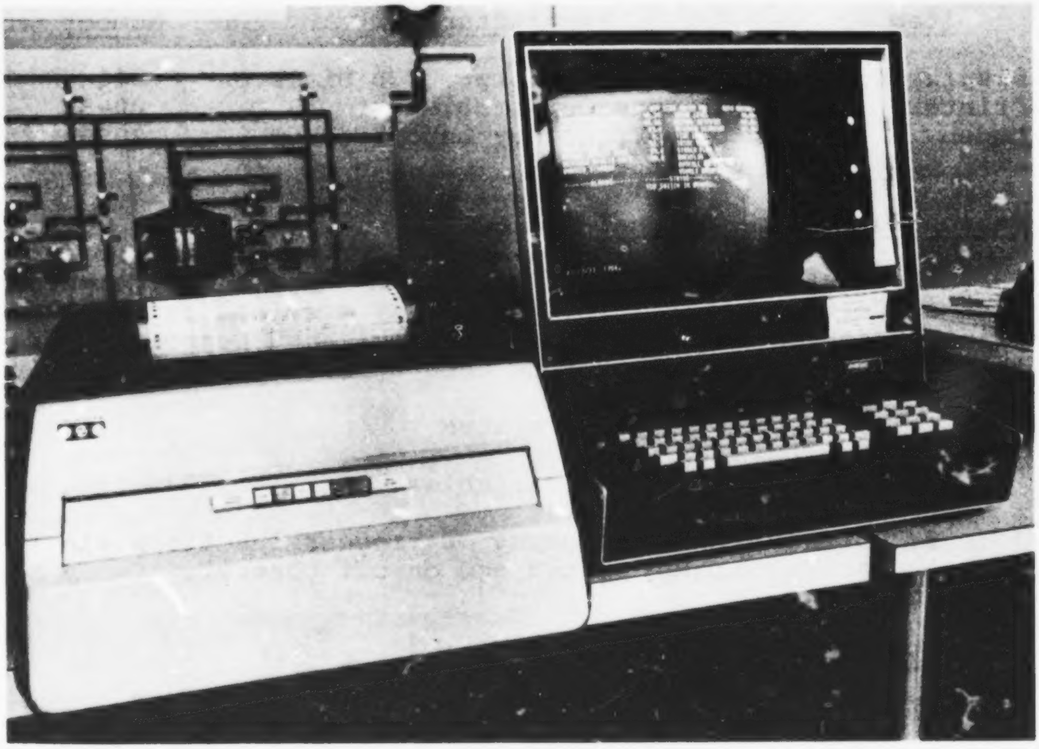


FIGURE 22

WEST POINT SATELLITE TERMINAL

CRT terminal display provides an ASCII character set with a capacity of 1536 character delay line memory and a 64-character solid state row memory. The display is refreshed at a rate of 60 refreshes per second. All communications control logic is built into the CRT terminal. The terminal input keyboard is arranged in standard typewriter format.

The printer speed is 15 characters per second with 72 print positions. The printer receives character input from the delay line memory under control of the CRT display logic.

A list of equipment at the West Point Satellite Terminal is shown in Table 9.

Table 9. WEST POINT TERMINAL EQUIPMENT

Item	Manufacturer	Model Number
Display Unit	Philco-Ford Corp., WDL Division	D21
Printer	Teletype Corporation	R0-37
Modem	Radio Frequency Laboratories	2099

Renton Satellite Terminal

The Renton Satellite Terminal comprises a minicomputer with a communications interface, a CRT terminal and an ASR printer (see Figure 23). Additional planned functions for the minicomputer at the Renton Sewage Treatment Plant include:

1. Monitoring contact status
2. Monitoring analog variables
3. Direct digital control of process functions via analog output system and on-off controls.

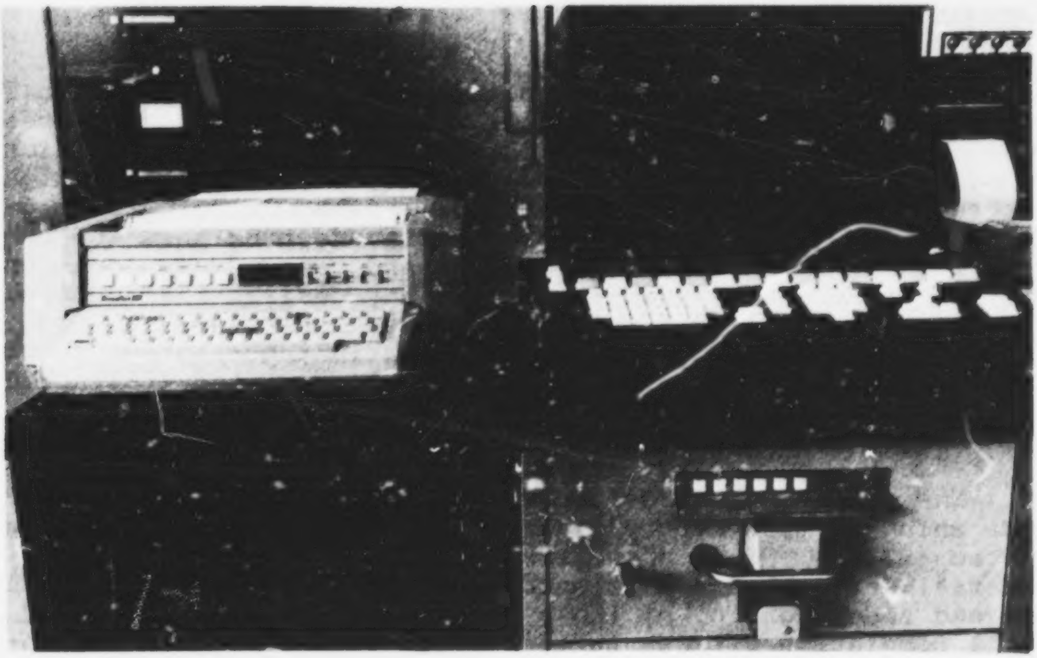


FIGURE 23

RENTON SATELLITE TERMINAL

A list of equipment at the Renton Satellite Terminal is shown in Table 10.

Table 10. RENTON TERMINAL EQUIPMENT

Item	Manufacturer	Model Number
Control Computer	General Electric	GE-PAC 3010-2
Printer	General Electric	Terminet 300
CRT display	General Electric	Datanet 786
Modem	Radio Frequency Laboratories	22DB

The central computer facility may be used to analyze process operations and initiate direct digital control operations via the satellite terminal.

Minicomputer -- The operation of the Renton Satellite Terminal is under control of a minicomputer which includes hardware features required for real-time applications, such as hardware interrupts, power fail safe and a real-time clock. The computer is also provided with a real-time programmed operating system. The basic unit of core storage is an 8-bit byte which is directly addressable on an 8-bit byte or 16-bit half-word basis.

Control of the central processor instruction execution is implemented through microprograms written into very high-speed read-only memory (ROM). The microprograms use ten basic microcoded instructions which are programmed to emulate the nominal instruction set available to the user. The microprogram accesses processor instructions from core memory, decodes them and processes them in the general registers and core memory locations. Microprograms can be used to emulate any desired instruction. The computer supplier has in this manner implemented a very extensive instruction set and an automatic input/output scheme. Actual user programming is done using the emulated instruction set, and the programs are stored in read-write core memory. Core memory access time is one microsecond.

The computer is provided with automatic input/output hardware which is used by the real-time multiprogramming operating system (RTMOS). Data transfers between the computer and an external device, once initiated by the central processor, will proceed under control of the automatic input/output system until completion without further processor action. The automatic input/output system signals the computer when a data transfer is complete through an interrupt. Thus while input or output is in progress with one task, the computer is free to process other tasks.

CRT Display -- The CRT Display has a capacity of 22 lines of 92 characters per line or a total of 2024 characters. The display controller uses a delay line memory to store the characters displayed on the terminal, which are refreshed 30 times per second.

The terminal keyboard is not arranged in a conventional typewriter pattern. Alphabetic keys are grouped together in alphabetical order, numeric keys are grouped into a 10-key numeric keyboard, and special character keys (punctuation, symbols) are in a separate group. The shift key permits dual use of alphabetic, numeric and special-character keys for additional punctuation and symbols. Transmit control and cursor keys are also included.

A special group of 15 action keys (expandable to 45) initiates transmission of the top line of the display and inserts a special two-character function code into the message. Each function code inserted by an action key can be interpreted by the computer as a specific request. These action keys are not presently used, but are reserved for implementation of direct digital control.

Printer -- The printer device includes a paper tape punch and a paper tape reader. The printer operates at a rate of 30 characters per second and can print up to 118 characters per line. Characters are transmitted to the printer in seven-bit ASCII code. The paper tape punch tape punch output eight-bit binary characters at a rate of 30 characters per second. The paper tape reader can input 8-channel characters at 30 or 120 characters per second. The printer does not print copy when the reader is in the high-speed mode.

Data Format

All data is transmitted as 10-bit characters, including a 7-bit ASCII code, a parity bit start and stop bits.

Data Transmission

All data transmission between the central control facility and the satellite terminals is under program control of the central computer. The central computer polls each terminal at regular intervals by transmitting a sequence of characters consisting of a start byte, two terminal address bytes and a command byte.

The command byte is interpreted by the satellite terminal as an instruction to enter either of two receive states or a transmit mode.

When no message is to be transmitted to the satellite terminal, the command byte places the terminal in a transmit mode. Unless the satellite terminal operator has requested message transmission by depressing the enter key, the satellite terminal responds to the poll by sending an end-of-transmission byte.

Upon receiving a command to enter the "erase/write" receive mode, the terminal erases the screen, positions the cursor in the upper left corner, and transmits a ready character to the computer, which initiated transmission of the text. If the command is to enter the "row address write" receive mode, the full screen is not erased and the first byte of the text contains a row index which positions the cursor at the beginning of the specified row.

Text including non-printing characters is received in a character string followed by a longitudinal redundancy character (LRC). The receiving terminal checks parity on each character which is received at the end of the character string. If an error is detected, an error byte is sent to the central terminal. If no error is detected, an acknowledge byte is sent to the central terminal, which returns a byte signifying end of transmission.

To transmit from the satellite terminal to the central terminal, the operator composes a message on the screen using the keyboard, terminating the message by depressing the "enter" key. If the enter key has been depressed, the satellite terminal responds to the next poll by transmitting a byte string comprising an address byte, text between delimiters, and the LRC character.

Information is written on the satellite terminal printer (when the satellite terminal is in a receive mode) by transmitting a "print" byte.

Central Station -- Data transmission equipment for each satellite terminal is interfaced to the computer direct input/output channel with identical interface logic. The interface equipment receives characters serially bit by bit from the modems and assembles them into parallel bytes for computer input. When an eight-bit byte has been received, the interface logic causes an interrupt to the computer, which reads the byte under program control.

Characters to be transmitted to either satellite terminal are output by the computer to the appropriate interface logic, which adds control bits and shifts the data out serially to the modems.

Satellite Terminals -- Although satellite terminal hardware differs, functional operation is similar.

Modems

Modems similar to those used by the telemetry system transmit data at a rate of 1,200 bits per second.

Communication Channels

Communications between the central station and each satellite terminal are over separate four-wire unconditioned Type 3002 circuits.

WATER QUALITY MONITOR INTERFACE

The Municipality's hard-wired water quality monitoring system was installed approximately seven years prior to procurement of the CATAD System. The existing water quality system monitors up to ten variables at each of five remote monitoring stations along the Duwamish waterway. The monitoring system central station equipment was interfaced to the CATAD system computer so that water quality data could be input directly to the computer. This data may then be stored for statistical analysis or used in the control system as one factor in determining locations where sewer overflows will result in the least adverse effect.

Water quality monitor data are input to the computer via the direct input/output channel using a specially designed interface. The interface processes messages character-by-character into the computer. Transfer is initiated by raising a ready signal in the water quality monitor equipment. The interface equipment receives and stores the first character in parallel form and interrupts the computer. In response, the computer executes a routine which reads the character into a storage buffer. Each character in the water quality message is handled similarly until the whole message has been entered into the computer.

REMOTE STATION MODIFICATION

Existing Local Station Controls

All regulator and outfall gate control stations were designed and constructed after 1961 and station controls were all of similar design, differing only in details to meet special station requirements.

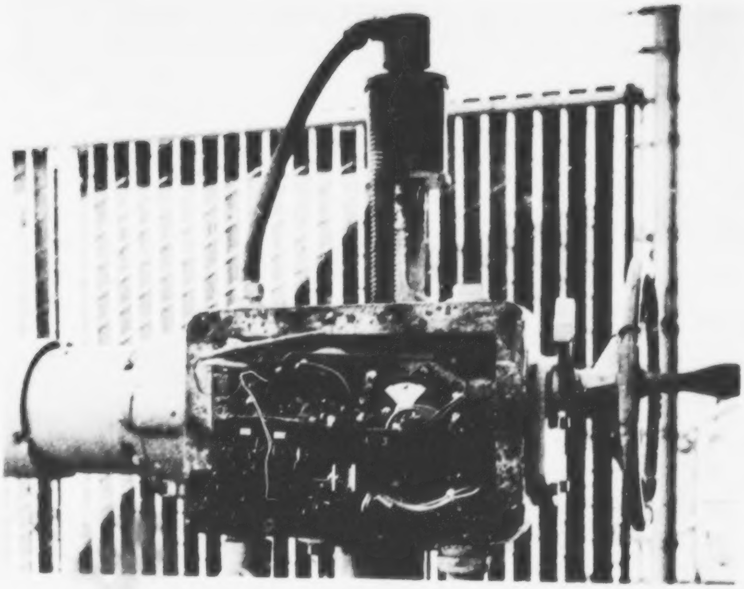
All pumping stations to which CATAD controls were applied were also designed and constructed after 1961. Older pumping stations in the original Seattle sewerage system were incompatible with the control system due to lack of backup storage or were in the process of being modernized. It was more economical to delay installation of the monitoring equipment than to modify these stations on an interim basis.

Types of Stations

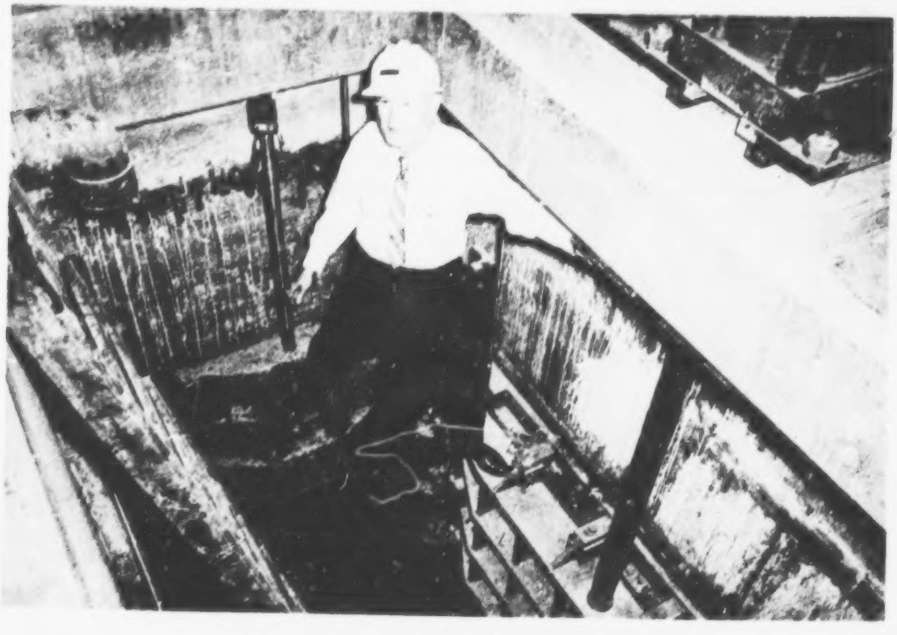
Remote stations designated for installation of control and monitoring equipment were regulator stations, outfall stations, combined regulator and outfall stations and pumping stations.

Regulator and Outfall Station Gate Modulation Power

In general, regulator station and outfall station gate movement (or modulation) is powered by a motor-driven gate operator (see Figure 24). Through gear reduction, the threaded shaft is turned and the sluice gate below moves up or down in response to the direction of shaft rotation. Four installations were provided with a medium pressure (750 to 1,500 psi) oil hydraulic power system wherein the gate is connected directly



A. PHOTO OF MOTOR AND GATE STEM



B. PHOTO OF SLUICE GATE

FIGURE 24

MOTOR DRIVEN GATE DETAILS

to a power piston that moves in a cylinder. Oil pressure is admitted either above or below the piston to produce gate movement.

Regulator Station Controls

The original regulator station controls were an electric contact controller with an adjustable fixed setting (setpoint) which it matched against a level measurement in the interceptor. The level was measured upstream of the regulator station to help avoid turbulence.

Several regulator stations designed to meet special criteria have overriding features or more complex control systems. These are Dexter Avenue regulator, Hanford No. 1 regulator and Lake City Tunnel regulator.

Outfall Station Controls

Outfall station controls are more complex than regulator station controls because they operate with more parameters and malfunction is more critical. The outfall gate limits the maximum trunk sewer storage level during high flow conditions by allowing overflow to the adjacent receiving water such as Elliott Bay. Excessively high levels in the trunk sewer may cause flooding of private property and excessively low maximum trunk levels limit storage, causing frequent unnecessary overflows. An added complexity is the tidal influence of the waters in the bay and estuary. Backflow of the tidal waters into the system must be prevented. The low elevation of the river delta land and resultant low elevation of trunk sewers with respect to maximum tide levels can cause the water level outside the gate to be higher than the normal trunk setpoint. The normal diurnal tidal range is about 11 feet. A prolonged storm can increase the water level several feet above normal. The difference between the record high and low tides is over 19 feet.

Pumping Station Controls

Pumping station controls were designed to operate either constant speed pumps with on-off control or adjustable speed systems. All but one of the pumping stations designed for the Municipality had adjustable speed operation for most of the pumps. One station has engine-driven pumps; one station has engine-generator drive for the largest unit; several stations have eddy-current couplings and several have liquid rheostat speed control.

Alarm Monitoring

Regulator stations, outfall stations and pumping stations were originally equipped with varying degrees of annunciator supervision to aid in detecting station problems. A tone telemetry system installed in 1965 was designed to give simple but effective reporting of two levels of trouble. Alarms were classified and connected as "priority 1" and "priority 2" status. Priority 1 alarms included power failure and in some stations, a high wet well condition. This system, termed "Metrotel," is still operating, but will be phased out in favor of the broader scope CATAD data collection system. Comparisons between Metrotel and CATAD monitoring capabilities are shown in the Operating Manuals, Volume III of this report.

OPERATION

Regulator Stations

The level signal from the upstream bubbler in the interceptor was (and is) the measured variable of the electric contact controller. The controller allowed the regulator gate to be wide open as long as the backwater interceptor level was below the instrument setpoint. However, if the interceptor level measurement reached the setpoint (plus a small differential or dead-band amount) the gate would begin to close. The gate would then either continue to close or modulate until the interceptor level arrived at a stable setpoint value. The gate might be in any position between fully open and fully closed to meet the setpoint requirement.

The setpoint was adjusted by Metro to approximately meet the expected interceptor flow requirements at the particular station. Since the Elliott Bay interceptor is the same diameter (42 inches) for several miles, the regulator farthest upstream (Norfolk St.) had a low setpoint (percentage full) and Brandon Street, the most northerly pre-CATAD station, had a high setpoint adjustment. It was not practical to readjust the setpoint for short term changes in weather conditions, so settings were picked for "eyeball" system balance, assisted by design calculations of system hydraulics.

Outfall Stations

The original control system utilized a single controller with auxiliary pneumatic control instrumentation equipment. The controller was a Foxboro large case electric contact unit with a pneumatically-moved setpoint. Trunk level was measured by a bubbler system and the reaction pressure fed to the instrument as the measured variable, which the instrument compared with the setpoint. If the measured variable (trunk level) was below the setpoint, control relays would close the outfall gate or, if it were already closed, would maintain the closed position. If the level exceeded the setpoint, the gate opened until the discharge flow lowered the level to the setpoint. The gate could modulate about the setpoint, but sufficient dead band was provided to prevent continual hunting.

The pneumatic setpoint was adjusted by a manual pressure regulator to a value considered safe for ordinary high water storage under any storm (flow) conditions. A pneumatic measurement of the upper range of the tidal level was made for each station affected. This signal was compared with the fixed setpoint signal by a sensitive pneumatic selector relay. If the tidal level approached within six inches of the manual setpoint level, the selector relay would substitute the tide level signal for the manual setpoint. A further increase in tide level would result in a corresponding increase in the setpoint signal to the gate controller, thereby maintaining a six-inch differential between the gate controller setpoint and the tide level. Under these conditions, the gate might be open (or partially opened) and only an outward flow could occur. The system proved very reliable and effective.

Pumping Stations

Pumping station control system operation differs too greatly from station to station to discuss in other than general terms. Station design criteria generally required adjustable speed drives and pumps were programmed in a lead-follow sequence allowing the influent sewer and set well depth level to vary in direct proportion to the flow. This allowed the influent sewer to be used for storage while maintaining a reasonably constant velocity in the sewer to provide adequate scouring.

At some stations limited usable storage in the upstream sewers, or Metro operational decisions, have introduced constant-level control systems. This is a minor controller change for stations with adjustable speed drives.

DESIGN CONSIDERATIONS

Storage Availability

The purpose of the CATAD system is to minimize overflows by utilizing available storage existing in the old trunk sewers. A study was made to determine the safe storage capacities of each major segment of the collection system. A summary of these data is listed in Table 3. Those stations with sufficient storage were labeled "command" station so that special remote control instruments could be installed to insure optimum utilization of that storage.

Four stations, West Michigan Street Outfall/Regulator, Harbor Avenue Outfall/Regulator, King Street Outfall/Regulator and Denny Way Local Outfall/Regulator, were found to have no usable storage. The Duwamish pump station was also designated a "non-command" station partly because of limited storage, and partly because maintenance considerations require good scouring sewage velocities in an inverted siphon upstream of this station.

Interface with Telemetry System

Instrumentation for the necessary analog and status information for transmittal was determined by studies and tabulations of both common and unique station requirements. Remote terminal requirements were first delineated. The tabulation and study resulted in five categories of regulator-outfall station remote stations and five pumping station categories. Definitions and functions of remote station equipment listed in the specifications are:

(1) Functions of Equipment -- The equipment will perform the following basic functions:

(a) Periodically collect operating data from remote stations and transmit contact position and feedback quantities from the remote stations to the computer.

(b) Transmit control signals from the computer to remote stations and transmit said data to the central computer.

All functions shall be under the control of the central computer.

(2) Classification of Remote Terminals

(a) Purpose of Classification -- The number of data items to be collected and transmitted from a remote station, and the number of control points at the station, will depend upon station operating functions. For the purpose of this work, equipment for pump stations and regulator outfall stations has been grouped on the basis of input and output requirements. The objective of the specifications is to procure modular equipment so that, insofar as practicable, equipment at stations of all classifications will be identical.

(b) Regulator-Outfall Stations -- Five remote station classifications for regulator-outfall stations have been assigned:

1. Type R01. Includes combined outfall regulator stations with storage capability. Storage regulation is accomplished by direct control of the regulator gate position using raise-lower contacts in the motor control circuits to regulate the amount of flow diverted from the trunk to the interceptor. Indirect control of the outfall gate is effected through control of trunk water level setpoint by raise-lower contacts in circuits controlling pulsed input to a stepping motor.

2. Type R02. Includes separate regulator-outfall stations having storage capability and provided with common telemetry equipment. The distance between the outfall and regulator stations is not greater than 1,000 feet. The Municipality installed a multipair individually shielded cable between the outfall and regulator stations so that a single TCU could be installed at the outfall station. Control operations are the same as R01 remote stations.

3. Type R03. Includes combined regulator-outfall stations having no storage capability. Remote control is accomplished through direct control of the regulator and outfall gate positions via raise-lower contacts in the gate motor control circuits.

4. Type R04. Includes the Denny Way regulator outfall at which two trunk lines feed into the interceptor. One trunk line has storage capacity, the second line has no storage capacity. The position of the diversion gate from each trunk to the interceptor is directly controlled. The outfall gate for the local trunk (no storage) is directly controlled. The outfall gate for the Lake Union trunk (with storage) is operated through control of the trunk water level setpoint.

5. Type R05. Includes regulator stations having storage capability with no outfall. Storage regulation is effected by direct control of the regulator gate position.

(c) Pumping Stations -- Five classifications for pumping stations have been assigned:

1. Type P1. Includes pumping stations with three electrically-driven pumps having storage capability in the conduit upstream of the station. Storage regulation is accomp-

lished by indirect pump control through a simulated water level signal to existing control equipment in place of the local control signal from a wet well level bubbler device.

2. Type P2. Includes pumping stations with three electrically-driven pumps and having no storage capability in the conduit upstream of the station. The equipment is used only to monitor station variable and alarm conditions.

3. Type P3. Includes only the Interbay pumping station with three gas engine-driven pumps having some storage capability in the conduit upstream of the station. Control is effected in the same manner as Type P1 station.

4. Type P4. Includes only the Matthews Park pumping station. This station has six electrically-driven pumps. Electric power is supplied internally from diesel engine generators or from an external power supply. Control is accomplished in the same manner as for Type P1 stations.

5. Type P5. Includes pumping stations with four electrically-driven pumps and having no storage capability in the conduit upstream of the station. The equipment is used only to monitor station variable and alarm conditions.

The foregoing classifications determined the instrumentation requirements in each station. It was decided at the time the equipment was specified that the computer system manufacturer would assume responsibility for receiving and analog and contact status signals at receptacles located on Metro's panels near each TCU. Similarly, outgoing command signals would be delivered by shielded cable to Metro's receptacles. (During construction the interface point was moved to receptacles on the TCU in order to provide a cleaner TCU unit.) The decision meant that a system responsibility point was established with Metro responsible for delivering the necessary signals at the required voltage levels to the TCU. This interface allows computer system trained people to be responsible for computer equipment and facilities; and electrical and instrumentation system personnel to be responsible for contact status or analog signals from the equipment.

The system contractor, Philco-Ford Company, built a station simulator to synthesize station analog signals or contact closures. Concurrently, Metro constructed a TCU simulator to check out the station signal prior to connection with the TCU as explained in the calibration section.

This common interface point for all stations permitted Metro to prepare the stations to connect to the TCU's soon after the CATAD contractor finalized his TCU design.

Integration of Local and Remote Control Functions

The first phase of modification involved system design for control of the regulator and outfall gates. The second phase involved purchase of electronic gate controllers for the outfall gate controls (OGC's), and the third phase involved construction work to install OGC's and auxiliary contacts and relays.

The prime system design criteria were to allow the central computer to control gate movement at any or all times, and to allow each station to return to its own control system in the event of telemetry link failure.

These criteria posed no problem for regulator gates as there was no conceivable situation where continuous movement from some computer-held gate opening position to another position required to meet the fixed setpoint could cause damage or inconvenience to the system or personnel.

The outfall gates, however, posed an entirely different problem. The primary function of the computer control system is to optimize use of storage in the large trunk sewers for a particular condition. The computer-held level might be considerably above the conservative normal setpoint level. During high flow conditions the computer could hold the gate closed resulting in a trunk level above setpoint. If the telemetry link should fail, the excess water level would cause the gate to open and begin immediate discharge, which might be entirely unnecessary from the standpoint of trunk inflow. Given a few extra minutes the regulator gate could discharge the excess stored water into the interceptor. The concept of ramping the setpoint signal was developed to solve this problem.

Since the existing pneumatic control did not lend itself to ramping, a new electronic outfall gate control system was designed. The final design established a reference setpoint, set into the chosen electronic control system. When the computer is in control, the central processor moves the controller setpoint as required. If the computer link fails, local controls compare the momentary controller setpoint with the reference setpoint, and utilizing pulses that are always available, move the controller setpoint up or down to achieve balance between the setpoint signal and the controller setpoint reference signal.

The pulse rate is adjustable with each pulse representing about one tenth of a percent change in signal, permitting smooth ramping at any preset rate. The pulsing system operated very smoothly, but the pulses and associated relays caused electronic noise problems as discussed in Section VIII.

Design details of the system control instruments employed in remote installations are presented in Appendix H.

Monitoring Functions

After the basic control system operating data was established in the early stages of CATAD design, station characteristics were evaluated. In addition to the basic data required for computer control functions, provision was made to transmit information which would aid station monitoring. Much of this data was provided through station alarm contact status supervision. Additional data critical to early determination of localized electrical system failures is also transmitted as single point contact closures. Direct transmission of critical alarm information provides Metro operations personnel with much information that had not been available previously. The CATAD system will gradually displace the existing alarm system.

A number of special analog measurements were required in pumping stations including wet well level, pump speed, force main pressure, pumped flow, pump program signal level, and explosion hazard level. Special status points determine which pump is operating and which pumping mode is selected (lead, follow or second follow). Force main valve position is also monitored where applicable.

Accuracy

The accuracy of all existing measurements was carefully checked by direct level measurements to bring instrument calibration of the various stations into agreement with the system datum levels as explained in the calibration discussion. The specified 1/10 percent accuracy required of the telemetry system is not achievable with most field instruments. However, measurements were upgraded as much as practicable. Levels are measured with extremely accurate electronic differential pressure transmitters. Overall measurement accuracy is limited by the accuracy of the bubbler system which can be affected by air flow rate and water turbulence. The overall accuracy probably approaches about two percent of full scale measurement.

Some of the original pneumatic gate position transmitters were unsatisfactory. Later station design uses a potentiometer to provide position measurement. Although sufficient turns were provided for 1/2 percent accuracy, the dead band on both the pneumatic and potentiometer systems was found to be about 10 percent, making the readings useless. After a study of the gear train system, Metro suggested that the gate operator manufacturer make a slight mechanical change in the final elements of the train. Potentiometers installed in later gate operators have provided reasonably accurate position measurements. Overall accuracy is estimated at about three percent. Hydraulic gates required a more complex device to determine the gate position. In some installations that gate position transmitter is operated by a steel tape attached to the gate. The tape is wound on a spring-loaded reel which encloses the transmitter. While this system is capable of better than one percent accuracy, some operational problems have persisted.

Accuracy of most analog measurements is considered within three percent of full scale, except for the explosion hazard reading which in many stations is far outside the accepted limits of dependable information. Pump speed readings were initially unreliable, but precise calibration equipment developed by Metro's engineering staff provided the necessary standard to allow accurate calibration of most existing tachometers.

Shielding and Grounding

Precautions were taken during design to provide pair shielded cables for all analog signals transmitted to the TCU. The systems contractor requested that all analog signals be grounded at the TCU to shorten the total scanning time. This request was approved by Metro and all instrumentation system designs met this requirement. Shields were grounded at the signal source end only. All enclosures were grounded to the station ground.

Design Problems

One principal design problem encountered in the analog instrumentation systems was the lack of internal isolation (input-to-output electrical isolation) in many units. For example, the high signal selector used in the outfall control system is not isolated, requiring addition of isolation amplifiers in the output circuit and one of the two input circuits.

Within a few years much of the complex control system now assembled from standard industrial instrumentation units probably will be more effectively built to order from solid-state component parts.

CONSTRUCTION

Regulator and Outfall Station Construction

The first phase of regulator station construction was to provide stations scheduled for new outfall gate controls with electronic control systems to replace the existing pneumatic systems (see Figure 25). The primary purpose was to obtain early recording levels to aid in programming the CATAD system which was already under contract. Nine wall mounted outfall gate controller units were purchased under Contract M23-67: Supply, Delivery and Calibration of Electronic Control Equipment and Accessories. Each unit contains a 3-pen recorder.

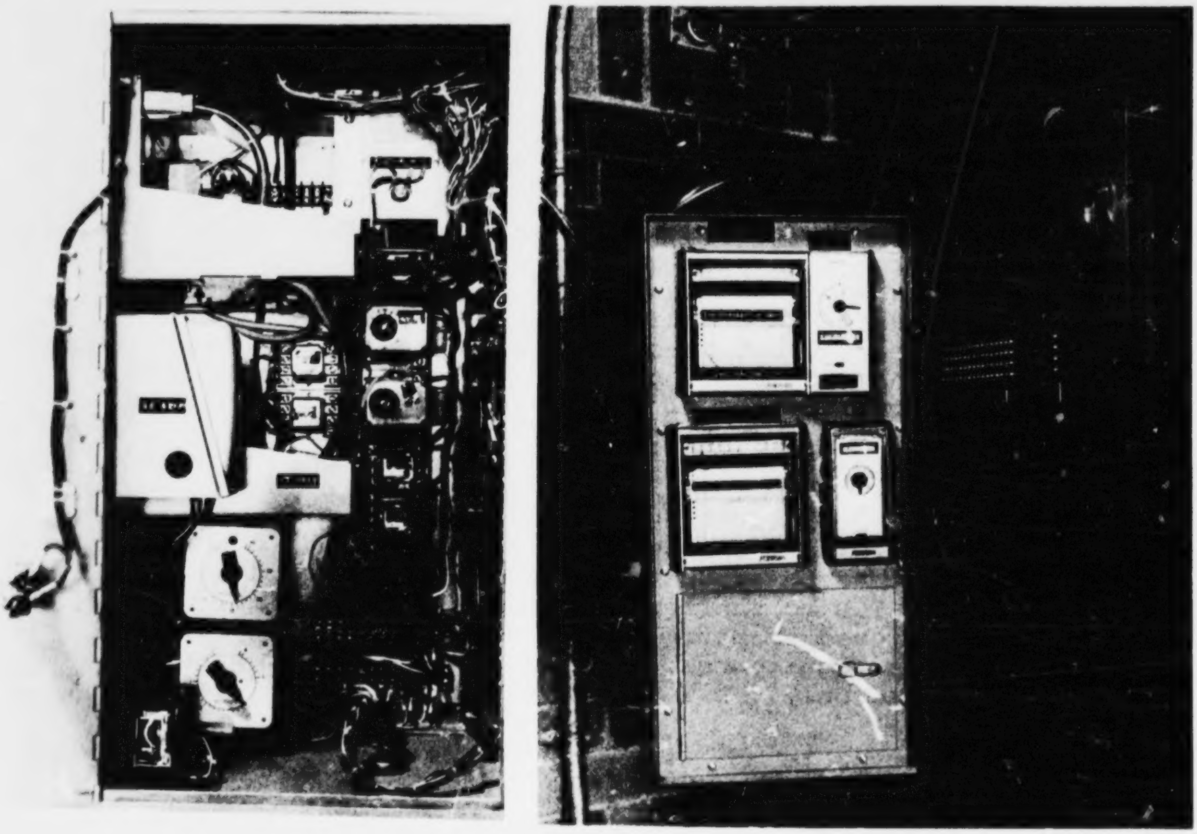


FIGURE 25

OUTFALL GATE CONTROLLER

A second contract provided installation of the outfall gate controllers and modifications to both outfall and regulator stations to provide signals to and controls from the telemetry control units. This contract, M10-69, CATAD Electrical Interface Equipment, covered installation work in nine stations. Controls were installed in the Norfolk Regulator in 1972 when the station was rebuilt. Controls were added to the existing construction contract for Denny Way Regulator/Outfall station by change order. Other regulator and outfall controls were incorporated during design stages including controls for King Street, Connecticut Street, and Hanford Street No. 2 regulator and outfall stations.

Pumping Station Modification

Contract 70-6, CATAD System Pumping Station Interface, was issued to provide central computer system control and monitoring facilities and connections in Metro's pumping stations. Six westside pumping stations were provided with control equipment to permit their influent sewers to be utilized for storage in conjunction with the trunk sewers of the Elliott Bay and North Trunk systems. Monitoring facilities were provided for the West Point Treatment Plant.

Seven Renton Division pumping stations were provided with monitoring facilities only. These stations and the Renton Treatment Plant report flow, pump speed and level indications to the CATAD system.

The contract was unique because of the small ancillary devices required to make proper connections to existing equipment. The contract provided the instrumentation and electrical work design for each station and required the contractor to supply and install all devices. He was required to quote a unit labor price for installing and a percentage markup for purchasing unspecified relays, contact blocks and devices, and for replacing and rewiring existing devices not applicable to the new system. This work, closely supervised by the resident engineer, saved many man-hours of "as-building" existing facilities prior to bidding. Precise "as-building" of each station prior to issuance of the contract might have delayed the modifications by more than a year. Field checks made during design insured that no major long delivery items were overlooked. The designer assumed that relay contacts were available on existing relays as indicated in Metro's office data. When actual conditions were found to differ, it was possible to perform the necessary modifications at a predetermined cost.

All work in pumping stations then under construction was included in the particular construction contracts.

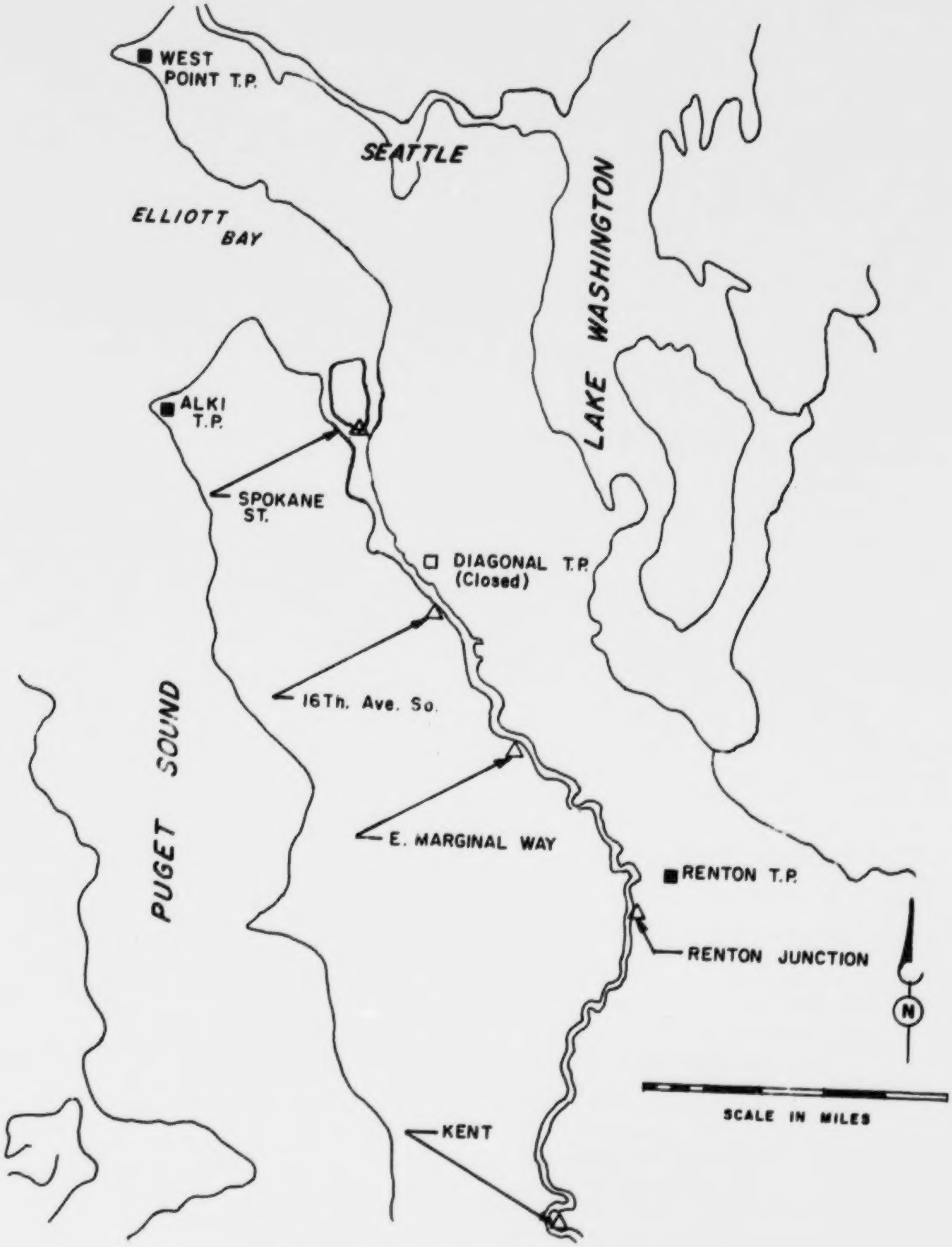

WEST POINT T.P.
SEATTLE
ELLIOTT BAY
LAKE WASHINGTON
ALKI T.P.
SPOKANE ST.
DIAGONAL T.P. (Closed)
16Th. Ave. So.
PUGET SOUND
E. MARGINAL WAY
RENTON T.P.
RENTON JUNCTION
N
SCALE IN MILES
KENT

FIGURE 26

AUTOMATIC MONITOR STATIONS

DUWAMISH RIVER ESTUARY WATER QUALITY MONITOR

Operation of Remote Recording Water Quality Monitor Stations

Remote Water Quality Monitoring Stations are located at five strategic locations on the Green-Duwamish River (Figure 26). These station samplers telemeter water quality data over controlled intervals (usually every 60 minutes) to the central computer where it is stored for processing. Monitor samplers consist of pumps, lines, reservoirs, flow cells, analyzers, probes, strip chart recorders and telemetry transmitters. The sampling units are housed in concrete block houses (Figure 27)

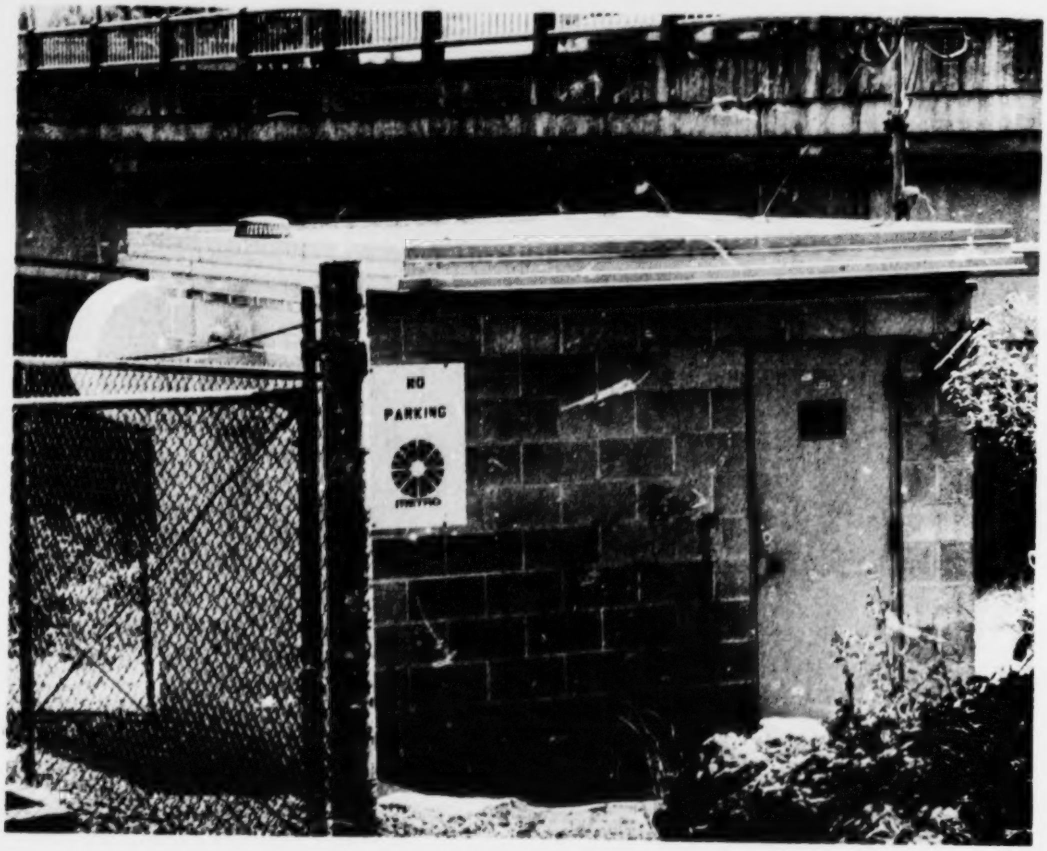


FIGURE 27

BLOCKHOUSE FOR MONITOR

at each sampling site to protect them from the elements and vandalism. The lines, floats and pumps have to be placed so that they are not readily accessible to the public (Figure 28).

FIGURE 28

MONITOR PUMP AND FLOAT

Surface pumps are attached to floats at least one meter below the waterline. Bottom pumps are kept one meter from the river bottom. These are located as close to the middle of the river channel as possible to assure a steady flow of water to the monitor station. These stations also include a mini lab and work bench for manual chemical analysis and minor repair.

Constant monitor temperature must be maintained for proper equipment operation and to ensure good telemetry of data to the central computer.

Analyzer readings are continually recorded on strip charts to ensure data availability in the event of telemetry failure.

Data Transmission and Storage

Data is transmitted to the central computer over leased telephone lines and stored on a permanent magnetic disk file large enough to hold four days of data. The disk file has this capacity so that the data can be handled automatically and retained until it is practical for the computer operator to copy the file onto cards for subsequent analysis and storage.

Data Compilation

Analysis of the monitor data is accomplished through a series of computer programs. The first step obtains a listing of all data for one month, simultaneously correcting the DO for conductivity and eliminating data whose test signal does not fall within the range 950-1050. The test signal proves whether or not the remote station transmitter is correctly adjusted.

Plots are then made of DO and temperature to assist the operator in detecting malfunctions such as pump outages or probe failures. These malfunctions are then compared with the regular weekly maintenance records of the remote sites. Unusable data is removed from the file, and unstable data due to linear probe drift is corrected so there are no discontinuities. Another plot is then made of the corrected data and a statistical summary is produced for regular water quality reports and distribution to USGS and others currently involved in modeling the Green Duwamish River estuary.

The corrected data is stored on magnetic tape for future investigation of long-term trends in river water quality (discussed in Section VIII) and as historical record.

Data Transmission, Interface and Storage

Data is transmitted to the automatic water quality monitoring equipment at the CATAD control center over leased telephone lines where, originally, the data was converted to characters printed on a hardcopy printer, and punched into paper tape. As part of the CATAD contract, this equipment was interfaced to the CATAD system computer so that water quality data could be input directly to the computer.

Water quality monitor data are input to the computer via the direct input/output channel using a specially-designed interface. The interface processes messages character-by-character into the computer. Transfer is initiated by raising a ready signal in the water quality monitor equipment. The interface equipment receives and stores the first character in parallel form and interrupts the computer. In response, the computer executes a routine which reads the character into a storage buffer. Each character in the water quality message is handled similarly until the whole record (including all data from one station) has been entered into the computer.

Data Use by CATAD

The river monitor data stored on the magnetic disk file is now available for real-time computer program scanning. The river data is scanned hourly by a program, arranging it into a report which is printed out on the console logger (see Figure 29). Under each station name the top line of data refers to river surface samples; the second line refers to bottom samples. Column headings beginning with "C" are conductivity levels and S.R.I. means solar radiation intensity, measured only at the East Marginal Street Station.

The Water Quality log performs two functions:

1. It helps the console operator decide if overflow priorities should be shifted to prevent discharging high BOD concentrations to a river area already critically low in dissolved oxygen.
2. It assists the monitor maintenance personnel in locating station problems which are highlighted with special code words.

There have been no critical river situations since this log has been on line, but the system is capable of providing future river environment protection.

Other on-line uses of the automatic river monitor data are being considered. A special cathode ray tube display would provide instant access to monitor data by either central or remote console operators. An alarm lamp and message printout would provide rapid warning and reaction to any monitor condition or river situation which might require operator decision or maintenance actions.

```
06/18/72  1700  WATER QUALITY HOURLY LOG
SURFACE          TEMP   02400  024000    D.O.     PH   S.R.I.
BOTTOM           TEMP          048000    D.O.

RENTON JUNCT.    060.1   0114   00000   09.24   06.82

[illegible]      060.7   0392   00240   07.92   07.07    0.01

16TH AVE. S.     058.6   0001   14680   09.28   07.46
                 054.2          40760   08.32

SPOKANE ST.      057.6   0001   37360   09.78   08.00
                 051.1          41800   10.42

WEST             060.4   0102   00240   09.44   07.21
```

FIGURE 29

CATAD RIVER MONITOR LOG

Monitor data directly linked to the control model was one of the original project proposals. Overflow loading effects would be predicted with a river model which would automatically adjust overflow priorities in the CATAD control model. Since tidal estuary modeling complexities are well known, it was determined that this effort would better be handled by an agency familiar with this type of activity. As part of a cooperative agreement, Metro and the regional branch of the United States Geological Survey will complete development of the river model. Indicating the difficulty of estuary modeling, this project was in progress prior to CATAD project initiation in 1968.

SECTION VI

OPERATING PROCEDURES

CENTRAL CONTROL FACILITY

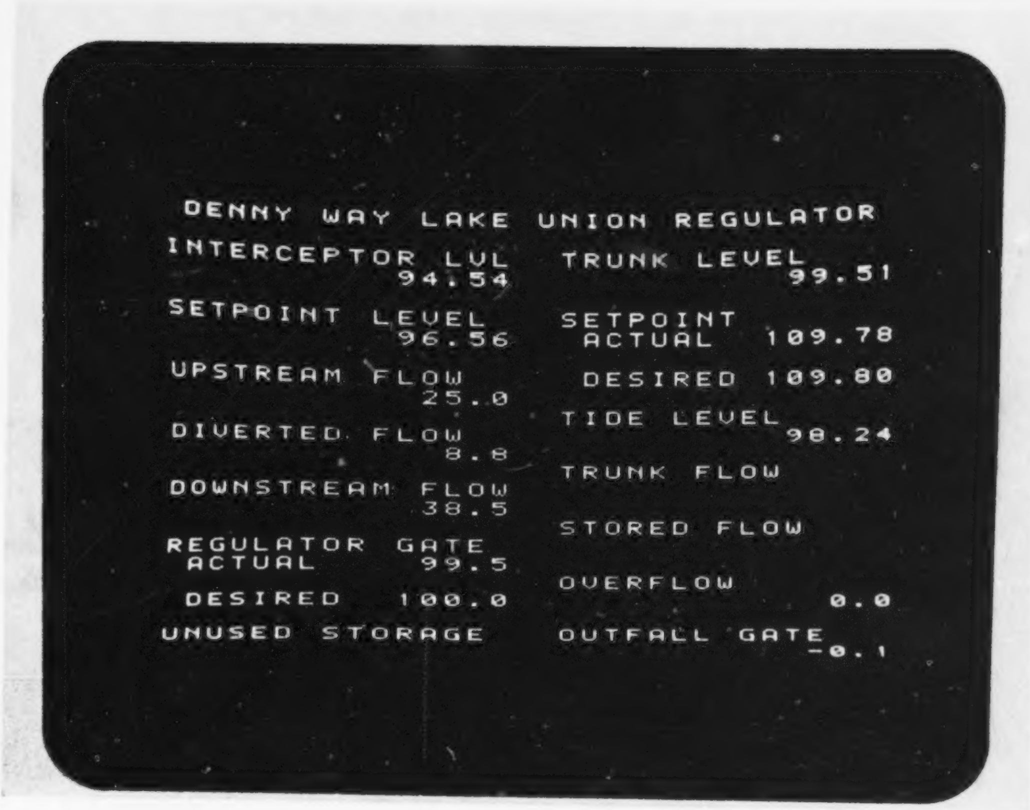
This section summarizes routine maintenance and operational tasks which keep the CATAD system running at the best possible performance during a trying developmental period.

Specific details such as logs, command procedures, etc., are itemized in Volume V of this report.

During normal working hours, the console operator is responsible for proper operation as discussed in the following paragraphs.

Observations of Console Display Data

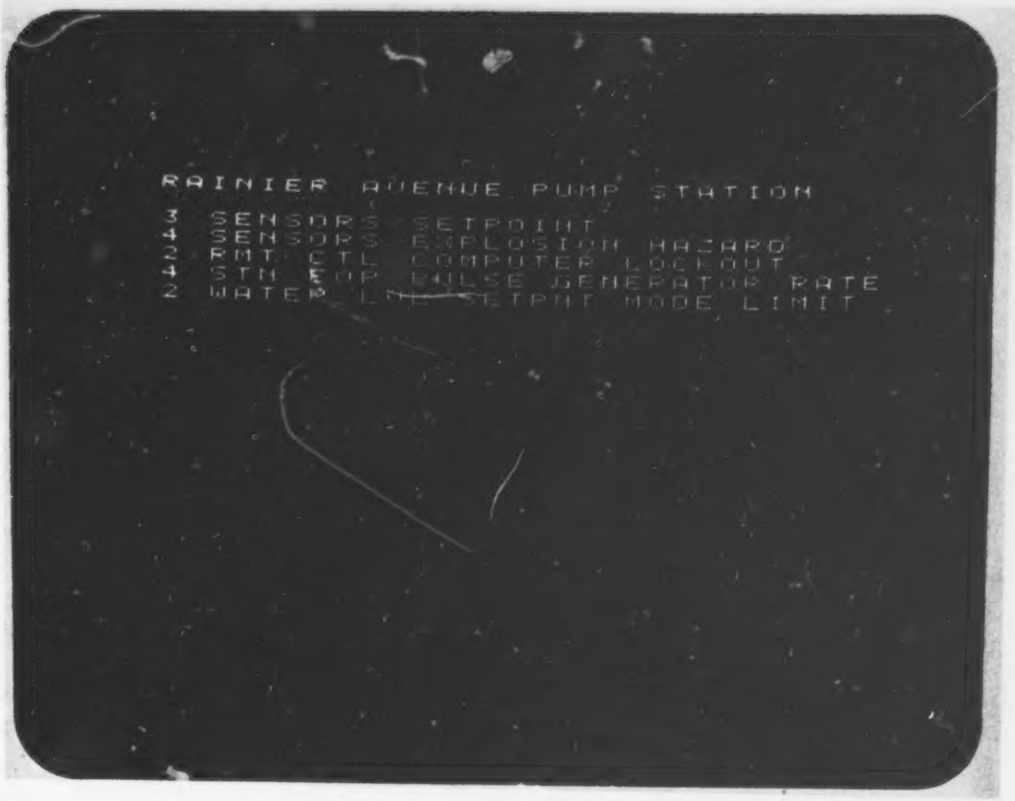
The console operator has seven cathode ray tubes (CRTs) for visual display of station data. The console arrangement allows display of one to seven different stations in a given geographical segment. By selecting the various segments, the operator can display all system stations. The CRT station hydraulic display (see Figure 30) provides the operator with current information about gate positions, trunk and interceptor levels, control setpoint positions, and flow figures for regulator stations; in addition, it shows wet well level, flows, setpoint position and pump speeds for the pumping stations. Stations are scanned and station information updated at regular intervals by the computer. The console operator enters the scan interval at the console so that the stations can be scanned at intervals of one minute, two minutes, five minutes, or even ten minutes. The operator also has two alternate CRT display formats available. The alarm format displays existing alarms at any monitored station in the system (see Figure 31). When this format is requested, the normal station data display is erased and station alarms are displayed on the appropriate screens. Selecting another segment (CRT display of other stations) automatically presents the alarm display format for stations in that segment. The third format displays total hourly rainfall in hundredths of an inch for stations with rain gages (see Figure 32). The rainfall display is automatically updated every ten minutes and reset to zero each hour. This format simultaneously displays current pulse counter rates, appropriate overflow volumes in million gallons per day, and values for explosive gas concentrations detected in the station. The display format remains fixed until the operator requests another format.



```
   DENNY WAY LAKE UNION REGULATOR
 INTERCEPTOR LVL    TRUNK LEVEL
           94.54               99.51
 SETPOINT LEVEL     SETPOINT
           96.56     ACTUAL   109.78
 UPSTREAM FLOW
           25.0      DESIRED  109.80
                    TIDE LEVEL
 DIVERTED FLOW                 98.24
            8.8
                    TRUNK FLOW
 DOWNSTREAM FLOW
           38.5
                    STORED FLOW
 REGULATOR GATE
  ACTUAL   99.5
                    OVERFLOW
  DESIRED  100.0                 0.0
 UNUSED STORAGE     OUTFALL GATE
                               -0.1
```

FIGURE 30

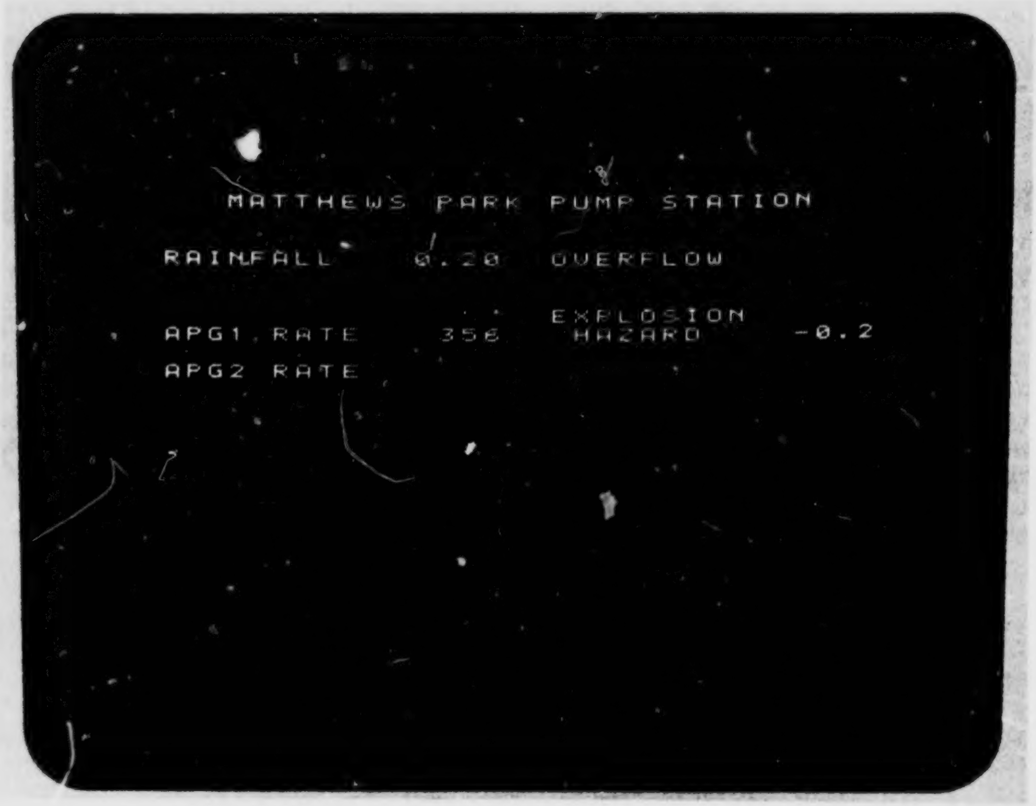
STATION HYDRAULIC DISPLAY



```
RAINIER AVENUE PUMP STATION
3 SENSORS SETPOINT
4 SENSORS EXPLOSION HAZARD
2 RMT CTL COMPUTER LOCKOUT
4 STN EOP PULSE GENERATOR RATE
2 WATER LVL SETPNT MODE LIMIT
```

FIGURE 31

ALARM DISPLAY



```
   MATTHEWS PARK PUMP STATION

RAINFALL      0.20  OVERFLOW

                    EXPLOSION
APG1 RATE     356    HAZARD      -0.2
APG2 RATE
```

FIGURE 32

RAINFALL DISPLAY

Two teletype units in the console room automatically log data from the remote stations. One teletype records all alarm and normal messages showing the station name, time the alarm is received or cleared, and the alarm description. Priority numbers have been assigned to certain alarm messages to indicate the necessity for immediate or postponed action. The same teletype unit also records all command messages entered from the console. The second teletype unit records hourly station data logs. This unit also records a storm log showing rainfall and overflow volumes. This log is printed only when rainfall is recorded or when an overflow occurs.

The information from the CRTs and teletype units enables the operator to monitor the remote stations, and review them for alarms. The teletypes operate 24 hours a day allowing the operator to review station data and alarms received when the console is unattended. After review, the operator determines which problems should be checked by maintenance personnel. The operator will determine, if possible, whether problems should be checked by treatment plant maintenance personnel, the telephone company, contract maintenance personnel, or engineers. The operator can often suggest possible solutions based on previous experience. The operator can then test equipment operation to determine whether repair is complete.

Data Storage

A variety of data forms generated manually and automatically by the CATAD system provide historical and reference information. The console operator accumulates and stores the following types of data:

1. Printed logs from the teletypes -- These logs provide information on station operation and are a permanent record of all control actions and alarms for the stations monitored.

2. During storm situations, magnetic tape is loaded to accumulate station data. This tape provides a record of the effects of various intensities of rainfall on the system and the effectiveness of control strategies.

3. The operator collects and stores reference data on the operational procedures and constraints for stations within the system. These records provide information to assist control decisions during storms; and provide a reference for determining the extent of possible remote station problems.

4. Manually prepared records indicate, by station, rainfall and/or overflows during storms. These records are useful for comparing various storms to determine control action efficiency.

5. Maintenance manuals are provided to facilitate adequate, effective repair when required. Equipment maintenance records are kept in remote stations and at the central control facility. These records describe solutions for problems which may recur, and help to determine whether a piece of equipment causing frequent problems should be modified or replaced.

Preventive Maintenance and Cleaning

The operator is responsible for general cleaning in the console and computer equipment rooms. Frequent cleaning is required to insure a dust-free computer room.

The operator maintains and files a preventive maintenance checklist for central control facility equipment. The list is filed when completed by maintenance personnel and is updated as required. The operator also files reports on routine and emergency maintenance performed on computer center equipment and certain station equipment. The operator purchases spare parts as needed, and maintains the spare parts inventory.

Compiling Reports

The operator prepares reports on problems or situations within the system. Since the CATAD system records data on many of the stations within Metro, it provides a source of information for solving problems or for justification of actions involving those stations.

The operator also documents additions or modifications to the system such as new alarm messages, procedures for reporting station problems, or equipment additions such as the recently added computer center fire protection system.

SUPERVISORY CONTROL DURING STORMS

The supervisory control mode provides for direct operator intervention in station controls during a storm situation. During the first 16 months of around-the-clock operation, supervisory control was the only alternative to independent station operation in minimizing or preventing overflows. Supervisory control requires an operator at all times to operate the console during storms.

The normal procedure for initiating and utilizing supervisory control is discussed in the following paragraphs.

Alerting CATAD Operator to Storm Situation

The operator is at the central control facility during regular working hours or is assigned on-call during nights and on weekends. Treatment plant personnel monitoring a remote terminal for alarm messages alert the on-call operator when the storm begins.

Operator Begins Supervisory Control

The operator first loads a magnetic tape to store remote station data during the storm. The operator then places the system on a one-minute scan interval so that station data is updated and stored on magnetic tape at one minute intervals. He places stations in supervisory control.

Flow Control and Storage Utilization

The operator then reviews the CRT displays and alarm status indicators for stations with existing or potential overflows. Existing overflows are stopped, when possible, by opening regulator gates and closing outfall gates to divert flow from the trunk into the main interceptor. Stations in local or independent control close the station regulator gate when the interceptor level reaches a designated setpoint, and keep the regulator gate closed until the level in the interceptor goes below the setpoint. The station then stores flow in the trunk behind the closed regulator gate. The flow remains in the trunk line either until the trunk setpoint level is reached and the outfall gate opens, or until the regulator gate opens. The console operator, through supervisory control, can open and close regulator and outfall gates to take advantage of additional storage capacity available either in the trunk or interceptor and, when required, the operator can command overflow at a selected station to relieve the system of excess flow. The operator can also control certain pump stations to increase or decrease the amount of flow going through the main interceptor at those stations. The operator puts the maximum flow through the station as soon as possible to gain additional storage in the interceptor during the early stages of the storm, and continues pumping maximum flow until the treatment plant flow capacity is reached.

A number of considerations determine where storage should be utilized, and when and where to overflow. Primary considerations are:

1. How much flow the treatment plant can handle -- Plant flow capacity can vary due to pump or engine problems, sedimentation tanks out of service, or a high tide level in Puget Sound affecting the amount of effluent that the plant can discharge.

2. Location and intensity of rainfall -- As a general strategy, the operator determines the area currently affected by the storm and attempts to store in non-affected areas. This procedure allows the maximum flow in the system to be directed to the treatment plant from the affected area. Storage in non-affected areas reduces the amount of flow going to the treatment plant through the entire collection system, and permits increased flow from the area receiving rainfall.

3. Tide levels -- A high tide level in Elliott Bay or on the Duwamish waterway can prevent opening an outfall gate when an overflow is required. The operator must anticipate peak high tides and allow for available storage during periods when some or all the stations in the system cannot overflow.

4. The operator is provided with listings of upper and lower interceptor, trunk, and wet well levels. Another list ranks the stations in order from least harmful to the most harmful overflow effects on receiving waters. The operator utilizes these lists to determine storage capacities, and to determine when and where overflows should occur.

5. Specific station problems may arise which limit the operator's ability to utilize supervisory control. These problems may arise prior to or during the period when supervisory control is attempted. The operator may or may not be able to make allowances for them. Specific problem details are covered in other portions of this report.

Release of Stored Flow

When the rainfall stops and flows begin to decrease, the operator can release flow stored in the system. The operator maintains the maximum allowable flow to the treatment plant without causing excessively high interceptor levels at stations from which flow is being released. The operator attempts to allow overflows only to stations at which the effects will be least detrimental. The operator may, for instance, stop overflows at three stations and intentionally overflow another station to maintain a balance of flow in the system.

Return Stations to Local Control

Releasing stored flow may require the operator to man the console for two to three hours after rainfall has stopped. The CATAD operator returns stations to local control when levels are sufficiently below setpoints to keep the regulator gates open and outfall gates closed. The operator can leave the console unattended with some stations still in supervisory control, when those stations are diverting flow from the trunk into the main interceptor at a rate which will not result in dangerous levels either in the interceptor or in downstream stations. The West Point operator can return the stations to local control from the satellite terminal.

AUTOMATED UNATTENDED OPERATION

The control mode alternative to "supervisory" control during storm situations places individual stations into the "automatic" control mode. A given station can be placed into "auto" control at any time, but only from the central console. Should the need arise, the West Point operator can, at any time, return the station to the "local" control mode.

The automatic control mode permits the computer to regulate flow in the system on a 24-hour a day basis. The automatic control program logic is presented in Section VII of this report. Auto control can remain active during dry weather flow periods when it will not attempt to store any flow in the system. Regulator gates are exercised during dry weather to maintain the bottom of the gate close to the varying water surface. This constant activity may be reduced later, but it is a good test of control program algorithms and provides early indication of mechanical problems permitting repair before a station must be employed in a critical storm condition. When a storm situation develops, increasing flows sufficiently, the system "automatically" begins storage based on maximum flow determined for the West Point Treatment Plant. As storm intensity increases, auto control regulates and stores flow to pre-determined safe levels, permitting overflows when and where they are needed. When flows decrease, auto control releases accumulated storage to maintain maximum safe flow levels in the system, thereby reducing or stopping overflows.

Console operator intervention is limited to changing the desired maximum flow figure for the West Point Treatment Plant as needed, and to changing the "rule curve duration" (time required for a station to achieve maximum storage utilization) for individual stations. Rule curve durations may be altered with different storms depending on the storm location and intensity and its effect on the system as a whole.

Auto control, therefore, has certain advantages over supervisory control, including:

1. Auto control provides immediate reaction to storm situations. In supervisory control, the storm situation must first be recognized by the on-duty treatment plant crew so that the CATAD console operator can be signaled by a radio device. Operational difficulties at the plant can interfere with storm recognition and delay the initial call to the console operator. On weekends or nights, the operator must then get to the console to begin control activities. Alertness and transportation factors affect the time delay before supervisory controls actually begin.

2. Auto control reduces the number of "judgment" decisions made by the CATAD operator. A supervisory control operator must be trained to spot and recognize potential problem situations such as dangerously high water levels; whereas auto control stores only to pre-determined safe limits which are stored within the computer memory banks.

3. Auto control reduces the chance of CATAD operator error in control strategy due to fatigue, inexperience, or lack of knowledge of the system.

MAINTENANCE EXPERIENCE

Maintenance tasks for the central control facility cover all the physical areas shown in the floor plan of Figure 33.

Computer Equipment Room

Most central facility preventive maintenance is performed in this area, which contains the main computer and peripheral equipment required for input and storage of programs and data. It also contains interfacing equipment for the remote and satellite station telemetry system. Preventive maintenance tasks are itemized by a stored computer program which provides a list for maintenance personnel. Maintenance task description and frequency are taken from the equipment manuals for each system component. Figure 34 shows a sample program output for daily maintenance work.

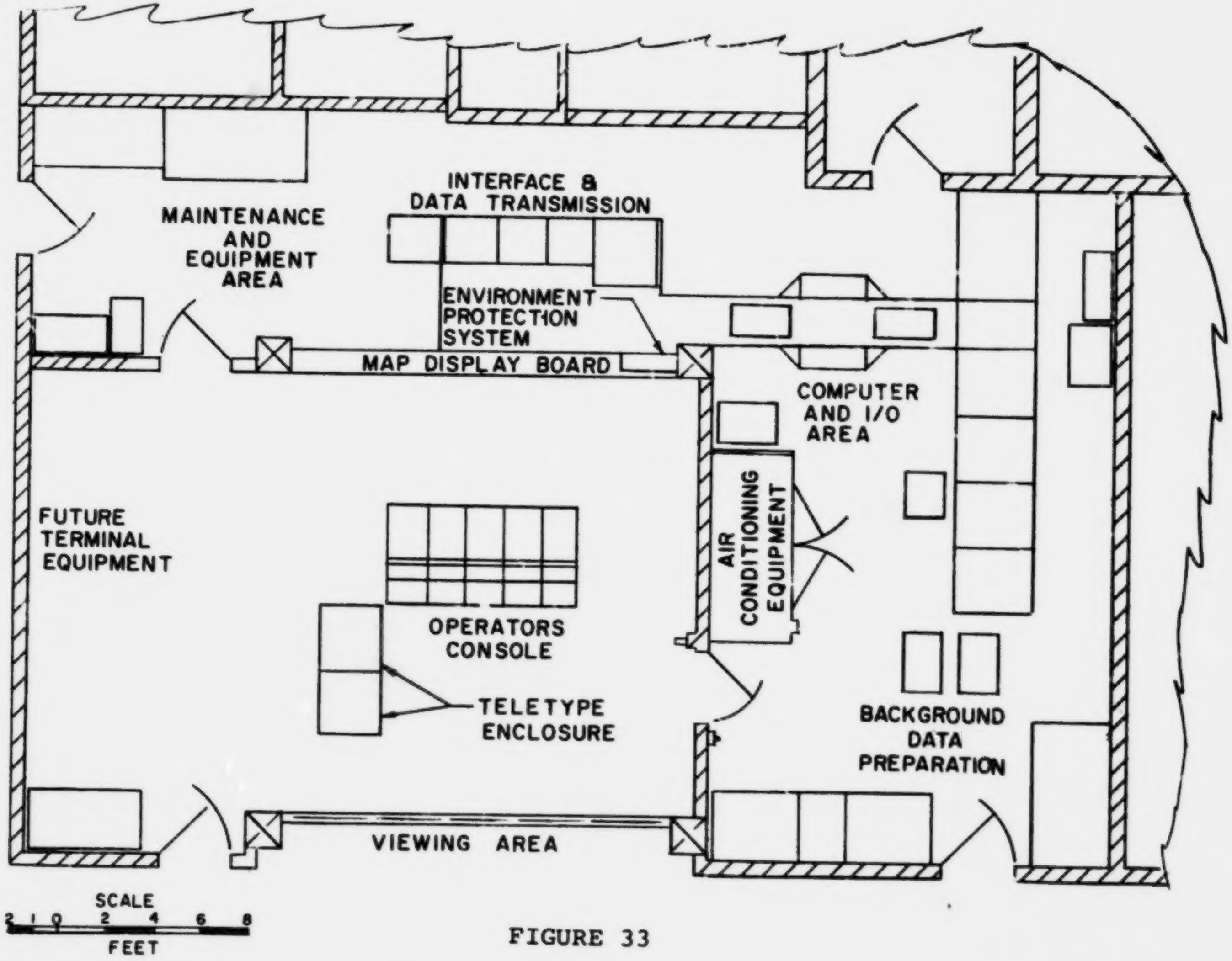

INTERFACE &
DATA TRANSMISSION
MAINTENANCE
AND
EQUIPMENT
AREA
ENVIRONMENT
PROTECTION
SYSTEM
MAP DISPLAY BOARD
COMPUTER
AND I/O
AREA
AIR
CONDITIONING
EQUIPMENT
FUTURE
TERMINAL
EQUIPMENT
OPERATORS
CONSOLE
TELETYPE
ENCLOSURE
BACKGROUND
DATA
PREPARATION
VIEWING AREA
SCALE
2 1 0 2 4 6 8
FEET

FIGURE 33

CATAD CENTRAL FLOOR PLAN

```
                    MONTHLY PREVENTATIVE MAINTENANCE SCHEDULE

    MAG TAPE DRIVE (TOP)                                          N. D. S.

-----CLEAN TAPE TRANSPORT

-----CHECK REEL HOLDDOWN ASSEMBLY

-----CHECK PHOTOSENSE HEAD ASSEMBLY

-----CHECK WRITE ENABLE ASSEMBLY

-----CHECK REGULATED POWER SUPPLY

-----CHECK CAPSTAN SERVO. = OFF-SET ADJ., TAPE SPEED, START-STOP RAMP

-----CHECK ALL TAPE MOTION FUNCTIONS


    MAG TAPE DRIVE (BOTTOM)                                       N. D. S.

-----CLEAN TAPE TRANSPORT

-----CHECK REEL HOLDDOWN ASSEMBLY

-----CHECK PHOTOSENSE HEAD ASSEMBLY

-----CHECK WRITE ENABLE ASSEMBLY

-----CHECK REGULATED POWER SUPPLY

-----CHECK CAPSTAN SERVO. = OFF-SET ADJ., TAPE SPEED, START-STOP RAMP

-----CHECK ALL TAPE MOTION FUNCTIONS


    LINE PRINTER, MODEL 744C                                      N. D. S.

-----VACUM COMPLETE HAMMER AREA

-----CLEAN AND CHECK VERTICAL FORMAT UNIT DRUM


    CARD PUNCH, MODEL 716C                                        N. D. S.

-----CHECK FOR BENT PUSHER FINGERS
```

FIGURE 34

DAILY MAINTENANCE WORK PROGRAM

A good preventive maintenance program should result in fewer equipment problems, and less "down-time" for the control system.

Periodically, equipment failures require repair work. Maintenance personnel must have ready access to spare parts and tools. The availability of such items usually determines how long the equipment remains "down." Maintenance personnel also need a current set of manuals for both hardware and software problem diagnosis. Computer availability has permitted Metro to computerize an inventory program for both spare parts and system documentation. Sample output from these routines appears in Appendix K.

Equipment failures often result from either excessive wear or heat. Temperature stabilization is achieved by an air conditioning system independent of the building air system. This system maintains constant temperature in the computer area while providing extra air cleaning capabilities. A regular preventive maintenance routine minimizes failures in this air supply system. The computer equipment is further protected by cooling fans in each unit to minimize the risk of overheating. The computer center fire and environmental protection system monitors the room temperature to initiate an alarm at 80°F and to shut down the central computer at 85°F. During unattended periods, these environmental alarms are transmitted to the two main treatment plants where the shift on duty has a call-out procedure for each alarm. Figure 35 shows some elements in the environmental protection system.

Computer Center Console Room

This area contains the console, mapboard, and two teletype units. The amount and complexity of equipment in this area is not as great as in the computer room. Most console room maintenance is performed on the teletype units. Monthly lubrication of the logging and event printers is required, as well as periodic minor parts replacements. A spare unit is kept on hand in case either "on line" unit should fail and require extensive, lengthy repair.

Other maintenance in this area is limited to cleaning filters for the console fan units, and periodic checks for unusual noises or equipment failure. Replacement lamps are kept on hand for the console and mapboard indicator lights.

An adequate stock of spare parts and written maintenance procedures are the most important elements in keeping an on-line process control system on-line. Continued operation and reduced major failure costs easily repay the time and money invested in a complete and well-supervised preventive maintenance program.

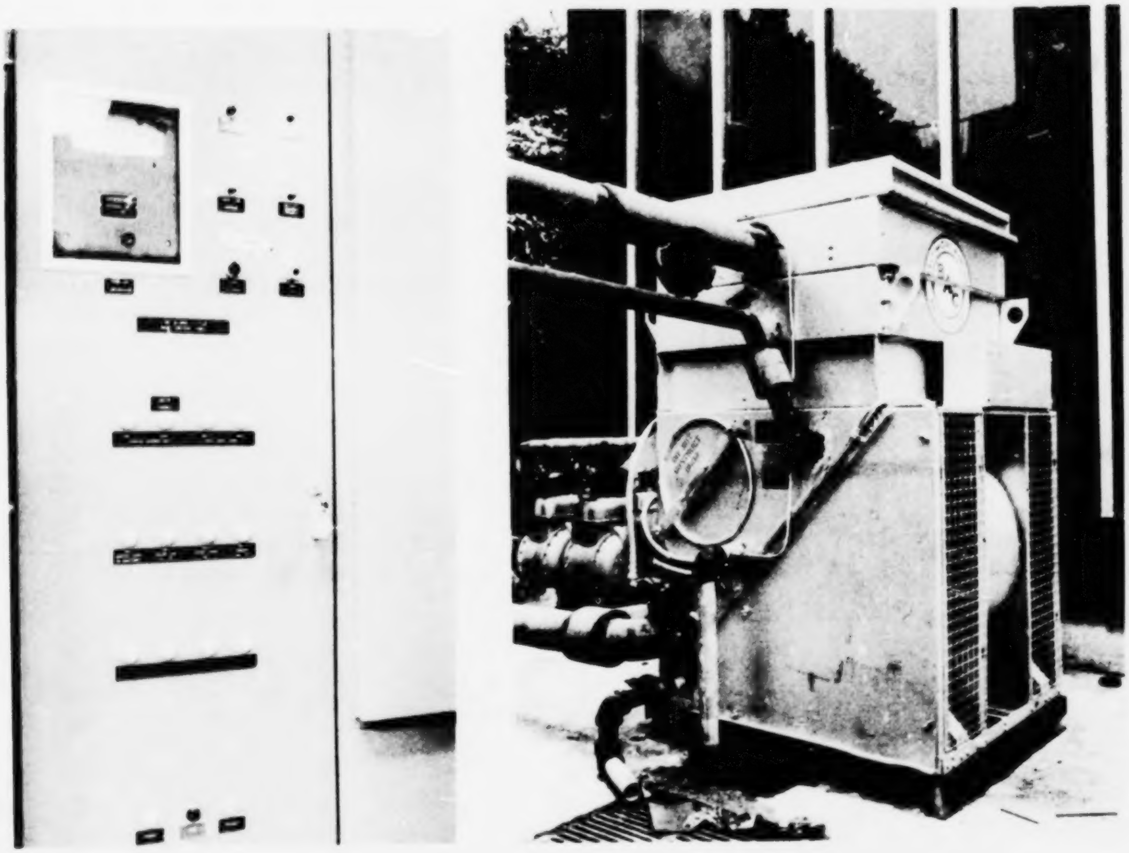


FIGURE 35

ENVIRONMENTAL PROTECTION SYSTEM

SATELLITE CONTROL FACILITIES

Surveillance

The two satellite facilities for the CATAD system are located at each of the main treatment plants (see Figures 22 and 23). Two facilities, located in the treatment plants, assure that the stations in the system will be monitored and surveyed around the clock. These facilities provide the operator with a cathode ray tube (CRT) display keyboard to key in commands and a teletype unit. The CRT displays the same data observed from the main console, and simultaneously displays the station control mode and shows alarm messages existing for that station. The teletype unit automatically prints alarm messages identical to those printed on the units at the main console, allowing the operator to identify station problems and to alert the CATAD operator or maintenance personnel as needed.

Controls

Theory of operation for the two satellite terminals is essentially the same. Both units permit the operator to key in a coded message and receive a visual display, a printed log, or a combination of both. Keyboard entry allows the operator to enter the following basic commands:

1. Display -- This command displays a requested station or a system of stations on the CRT. The operator can also request that all data displayed be printed on the teletype.
2. Alarm Review -- The operator can display, and print if desired, all current alarms for a single station or for a system.
3. Local -- The satellite operator can return a single station or an entire system to local control from either automatic or supervisory control.
4. Test -- The test command displays and prints (for some tests) a pre-determined set of characters. Six test sequences exercise the CRT and teletype unit to detect operating problems.
5. Cancel -- Cancels a previously entered command which the operator decides not to complete.

6. Maximum Flow -- Automatic control regulates the amount of flow entering the West Point Treatment Plant from stations within that system. Operating personnel determine the maximum flow, in million gallons per day, that the treatment plant can process at any given time and alter the maximum flow value as needed. Automatic control, in turn, releases or stores flow in the system to achieve the maximum flow desired.

Maintenance Experience

Satellite control facility equipment consists of a CRT, a teletype unit, and the telemetry circuitry to transfer data to and from the main computer. A preventive maintenance schedule has been established to check and clean the CRT and teletype monthly. Minor problems within the integrated circuitry of the CRT have been easily resolved. The teletype unit has proven reliable and has operated with few problems. The telemetry circuit, like others in the system, is utilized many times a day and has been very satisfactory. If difficulties arise, the telephone company can isolate the circuit address and perform what is called a "loopback" to test the continuity of the circuit. Loopback test results indicate the general location of the circuit equipment causing the problem and assist in determining whether the telephone company or our own maintenance personnel should investigate.

REMOTE STATIONS

The CATAD system is designed to monitor and control stations in the Metro system. Stations are basically of two types: regulator stations and pumping stations. Regulator stations utilize a set of mechanically operated sluice gates to control flow from the trunk line into the main interceptor. Pumping stations are located at positions along the interceptor to lift the flow to higher elevations.

Routine Procedures

During dry weather periods the operator is primarily concerned with monitoring alarms from the various stations and assisting maintenance personnel in checking problems. During dry weather periods, a number of stations operate independently of the CATAD control system in a "local control" mode (see Figure 36). A station in local control operates gates or pumps to regulate flow to specified safe levels. If the flow exceeds those pre-determined, fixed setpoints the station automatically stores and diverts excess flow until the levels drop to a safe point.

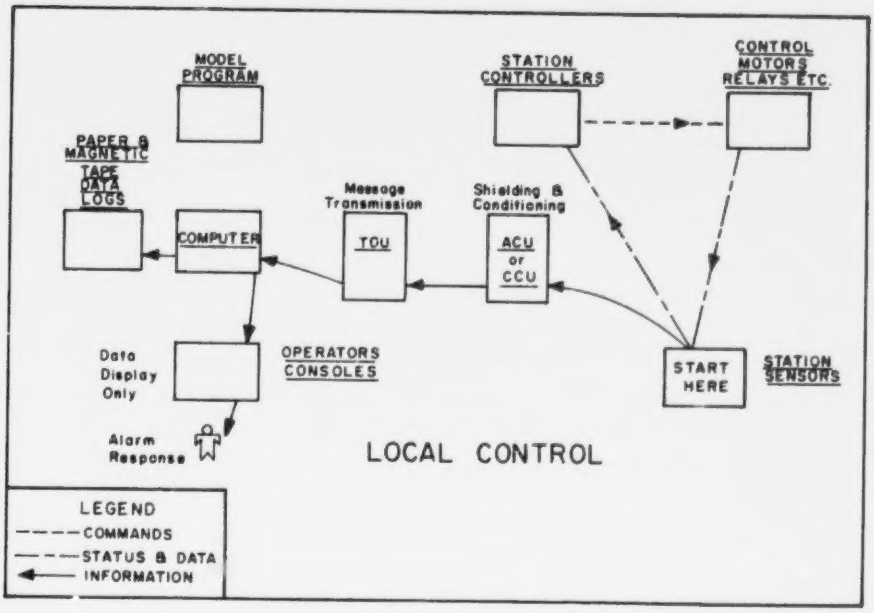

MODEL PROGRAM
STATION CONTROLLERS
CONTROL MOTORS RELAYS ETC.
PAPER & MAGNETIC TAPE DATA LOGS
COMPUTER
Message Transmission
TCU
Shielding & Conditioning
ACU or CCU
Data Display Only
OPERATORS CONSOLES
START HERE
STATION SENSORS
Alarm Response
LOCAL CONTROL
LEGEND
COMMANDS
STATUS & DATA
INFORMATION

FIGURE 36

LOCAL CONTROL

The CATAD operator can place a station into "supervisory control" to take advantage of extra storage capacity in the trunks and interceptor (see Figure 37). From the console the operator can monitor levels in the various stations and adjust gate positions or alter pump speeds to utilize maximum storage. The console operator contacts the treatment plant main control room to advise which stations should be placed in supervisory control. The plant personnel, in turn, alert the various pump crews as they radio in to check the stations. This practice prevents the loss of CATAD control in the station and prevents injury to any person already in the station.

The third station mode is "automatic control" (see Figure 38). In this mode the computer directly controls the gates in the regulator stations. The regulator gates are kept just above the water surface in the trunks until the flow increases sufficiently to require storage. The main treatment plant control operators are advised of stations in auto control or in supervisory control to prevent pump crews or other personnel from causing a loss of CATAD control in the stations. A station can be left in automatic control 24 hours a day, utilizing the system to its best advantage in dry weather or storm situations.

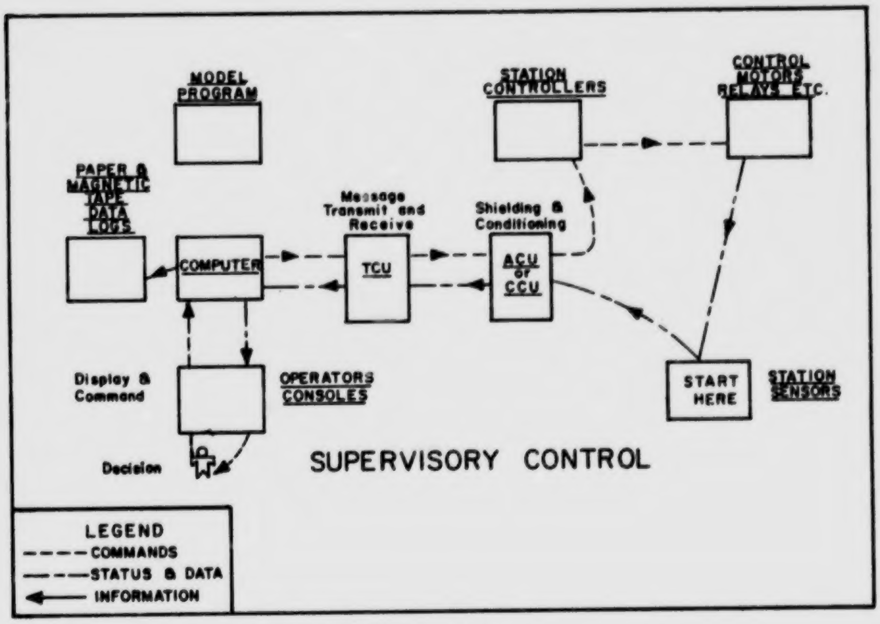

MODEL PROGRAM
STATION CONTROLLERS
CONTROL MOTORS RELAYS ETC.
PAPER & MAGNETIC TAPE DATA LOGS
Message Transmit and Receive
Shielding & Conditioning
COMPUTER
TCU
ACU or CCU
Display & Command
OPERATORS CONSOLES
START HERE
STATION SENSORS
Decision
SUPERVISORY CONTROL
LEGEND
COMMANDS
STATUS & DATA
INFORMATION

FIGURE 37

SUPERVISORY CONTROL

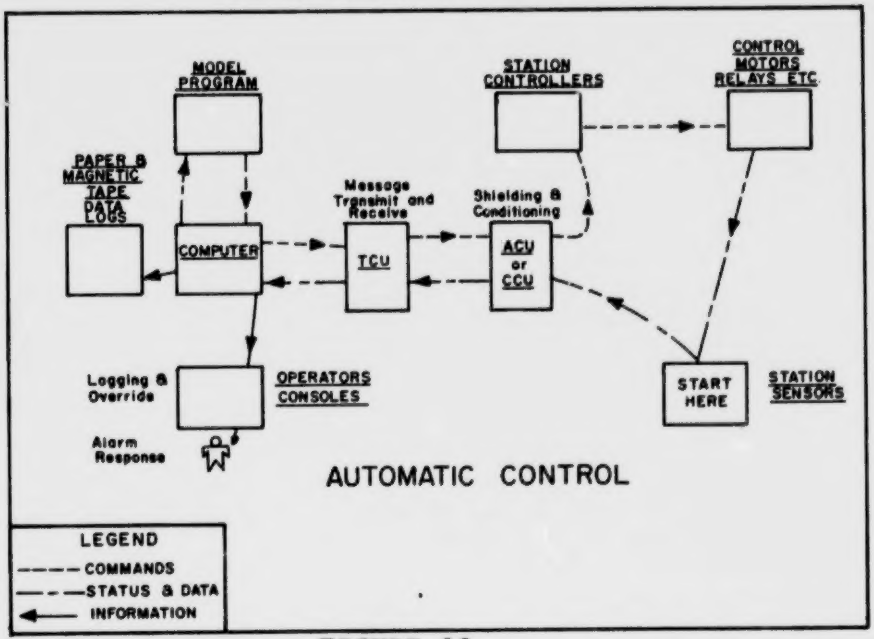

MODEL PROGRAM
STATION CONTROLLERS
CONTROL MOTORS RELAYS ETC.
PAPER & MAGNETIC TAPE DATA LOGS
Message Transmit and Receive
Shielding & Conditioning
COMPUTER
TCU
ACU or CCU
Logging & Override
OPERATORS CONSOLES
START HERE
STATION SENSORS
Alarm Response
AUTOMATIC CONTROL
LEGEND
COMMANDS
STATUS & DATA
INFORMATION

FIGURE 38

AUTOMATIC CONTROL

Pump crews assigned to each station check the various stations daily. Periodic tests are run on the air systems, emergency power, and hydraulic systems within the stations. Pump crews and maintenance personnel have been advised of procedures to follow upon entering a station so that automatic control or supervisory control is not lost.

Calibrations

A variety of sensing devices is utilized in pumping and regulator stations. The sensing devices require initial calibrations based on known reference data to insure accurate information about the stations and their equipment. The basic sensors are:

1. Tachometers -- Utilized on pumps to indicate their speed. Tachometers are calibrated so that the speed range, from zero to maximum speed, generates a predetermined electrical signal.

2. Explosion Hazard Detectors -- Designed to detect specific concentrations of various gases. The units are tested by exposing them to known gas concentrations and assuring that the required electrical signal is generated by the unit.

3. Air Bubblers -- A system of air lines and bubbler tubes are connected to detect pressure changes within the bubblers. The units indicate levels in wet wells, trunk lines, interceptors, and tide levels. Air bubblers are initially installed at a fixed height above a known elevation, such as a pipe invert, and all data generated is referenced to that point.

4. Linear Potentiometers -- Gate positions are indicated by linear potentiometers which produce a known voltage depending on wiper position on the potentiometer's inner windings. The voltage is converted to gate position in terms of percent-open, with a fully open gate shown as 100.00%.

5. Force Main Pressure Transmitters -- FMP transmitters are pressure-sensitive devices which indicate the pressure from the pumps into a force main. The devices are initially calibrated with a "pounds of pressure" reference and operate within a range preset in the unit. Pressure change on a diaphragm in the unit results in corresponding changes in voltage output.

Most Metro system pumping and regulator stations were constructed before the CATAD equipment was installed. Some system sensors were designed to perform within less critical tolerances than required for the CATAD system. Some sensors have been modified, and in some cases, the tolerance limits expected were enlarged to allow a margin for error. All sensors transmit data within a fixed span of two to ten volts. Sensor malfunction generates an alarm message so that the sensor can be recalibrated or replaced.

Maintenance Experience

CATAD equipment in each station has been divided into two basic categories to divide maintenance responsibilities. The first group covers the telemetry control unit and all equipment contained within it. The second group covers all other station equipment including the cables leading into the TCU. Responsibility is divided because TCU maintenance personnel know little about station operation, and plant maintenance personnel are unfamiliar with computer electronics. Maintenance experience in these two groups follows:

1. Telemetry Control Unit -- A preventive maintenance program has been established to run frequent tests on the basic components within each TCU in the CATAD system. The checks periodically result in minor adjustments to the modem, or frequency transmitting portion, in the unit. Equipment problems arising within the TCU can eventually be sensed by the main computer. Problems may arise which require replacement of a power supply or a micromodule within the TCU. Such problems cause transmission of bad data, or loss of data transmission altogether. The CATAD operator can alert maintenance personnel so that checks can be made on the appropriate TCU.

   Generally speaking, the TCU loses the command status of a station when there is a change in AC power to the unit. This can result when pump crews test the emergency power system in the station or during a surge in the normal power supply to the station. Emergency power systems are tested weekly by the pump crews. Test procedure is as follows:

   (a) Take the station off AC power.
   (b) Start the emergency generator. The generator will begin to run after a delay.
   (c) Test the generator and shut it off.
   (d) Return station to AC power.

The TCU command relays drop out, causing a loss of CATAD control, during the period between loss of station AC power and starting of the emergency power system. When the emergency generator system is started, the CATAD operator is able to re-establish station command and resume normal operation.

Another occasional TCU related problem is loss of telemetry between the central office and a remote station. Telemetry loss can result from a problem within the TCU or from telephone circuit difficulties. Test devices built into the system allow the CATAD operator and the telephone company to isolate the locaion of the problem, and determine who is responsible for repair.

2. Station Equipment -- Treatment plant maintenance personnel perform scheduled preventive maintenance on all stations within the system. In the process of performing these jobs, tests are made to detect possible problems in the station equipment. The CATAD system is designed to monitor critical station equipment and generates alarms when the equipment is not working properly. For the most part, problems are relatively minor and can be resolved easily. Some specific station equipment problems recur or are similar from station to station. Once resolved, these problems are more easily handled when they recur. Typical examples are:

   (a) Faulty Linear Potentiometers -- Regulator gate and outfall gate positions are indicated from linear pots. The wiper position on the windings produces a position indication of 0 - 100 percent gate opening. Periodically a pot winding will wear, resulting in an erroneous gate position transmission. For example, the gate may be fully open (100 percent) and the indicated position may be 85 percent open. When a station is in local control, the gate opens fully and automatically regardless of the indicated position. Supervisory or automatic control requires accurate gate position indication so that the gate can be regulated properly.

   Automatic control issues commands to the regulator gate to maintain a position just above the water surface in the trunk. As the trunk level drops during low flows, auto control issues a command to lower the gate position. Auto control then checks to assure that the actual gate position has moved to within two percent of the commanded position. A faulty potentiometer may indicate no change in gate position and auto control reissues the command. The gate actually does raise or lower depending on the command issued even though the indicated position does not change. This can create a critical situation if the regulator gate, following repeated commands to lower, moves to a fully closed position, stops all flow into the interceptor and raises the level in the trunk. A rising trunk level, in turn, can cause an open outfall gate and an overflow.

A revision has been made in the auto control commanding procedure to prevent such an occurrence. If after three command attempts there has been no change in the actual indicated position, the station automatically returns to local control. The gate opens fully and prevents overflow. The console operator can later return the station to auto control.

(b) Faulty Setpoint Controllers -- Two mechanical problems have arisen which have caused loss of setpoint control in both pumping stations and regulator station. These problems are:

(1) Regulator stations -- Setpoint controllers in some regulator stations control the trunk outfall gate, and a level below the setpoint keeps the gate closed. Supervisory or automatic control procedure raises the trunk setpoint levels when and where possible to take advantage of extra storage capacities during storms. A difficulty in several stations was caused by a faulty diode in the setpoint controller. The system could lower the setpoint level, but could not raise it. In each case, replacing the diode solved the problem.

(2) Pumping Stations -- Pumping stations utilize setpoint controllers to alter pump speeds when the wet well level raises or lowers. Both supervisory and automatic control utilize setpoint control to directly adjust pump speeds during storm situations. Increasing the pump speeds results in lower elevations increasing storage capacity, and decreasing the speed begins storage utilization earlier than would occur in local control. A setpoint controller problem can cause a loss of pump speed control for a station in local, supervisory, or automatic control. The problem has thus far been detected by a pulse

counter rate alarm. The pulse counter rate determines the rate at which the setpoint changes are made. The computer monitors the number of pulses or counts within a ten-minute period. When the pulse rate goes to zero, the setpoint is not moving and cannot be moved. Replacing the pulse counter solved this problem.

SECTION VII

PROGRAM DEVELOPMENT

GENERAL

CATAD system programming, like most real-time systems, falls into two principal categories:

1. Systems programs
2. Applications programs

Systems programs comprise the general routines for programming and operating the computer and general-purpose peripheral input and output devices, as well as special routines required for the hardware operation and data management functions of the specific hardware provided for data acquisition, data display and control. Applications programs comprise the routines related to the specific-process, including scaling, limit checking, alarming, storing measured variables, computing dependent variables from measured variables, logical process analysis, defining control sequences, and formatting logs and data displays. Figure 39 shows the organization of the major software elements.

SYSTEMS PROGRAMS

Systems programs include the following principal categories:

1. Operating System
2. Operating System Replacement Routines
3. Process Device Input and Output Interrupt Handlers
4. Real-Time Clock Routines
5. Executive System
6. Debug Facilities
7. Programming Languages

The computer manufacturer generally provides standard software for a general-purpose data processing computer system which includes bulk memory devices and conventional input and output peripheral devices. The CATAD system supplier has developed extensive software for the computer, including a highly sophisticated operating system intended for real-time application, as well as an assembler, a Fortran compiler and debugging aids. From time to time, the supplier releases new software versions which correct errors in previous versions, or extend system capability.

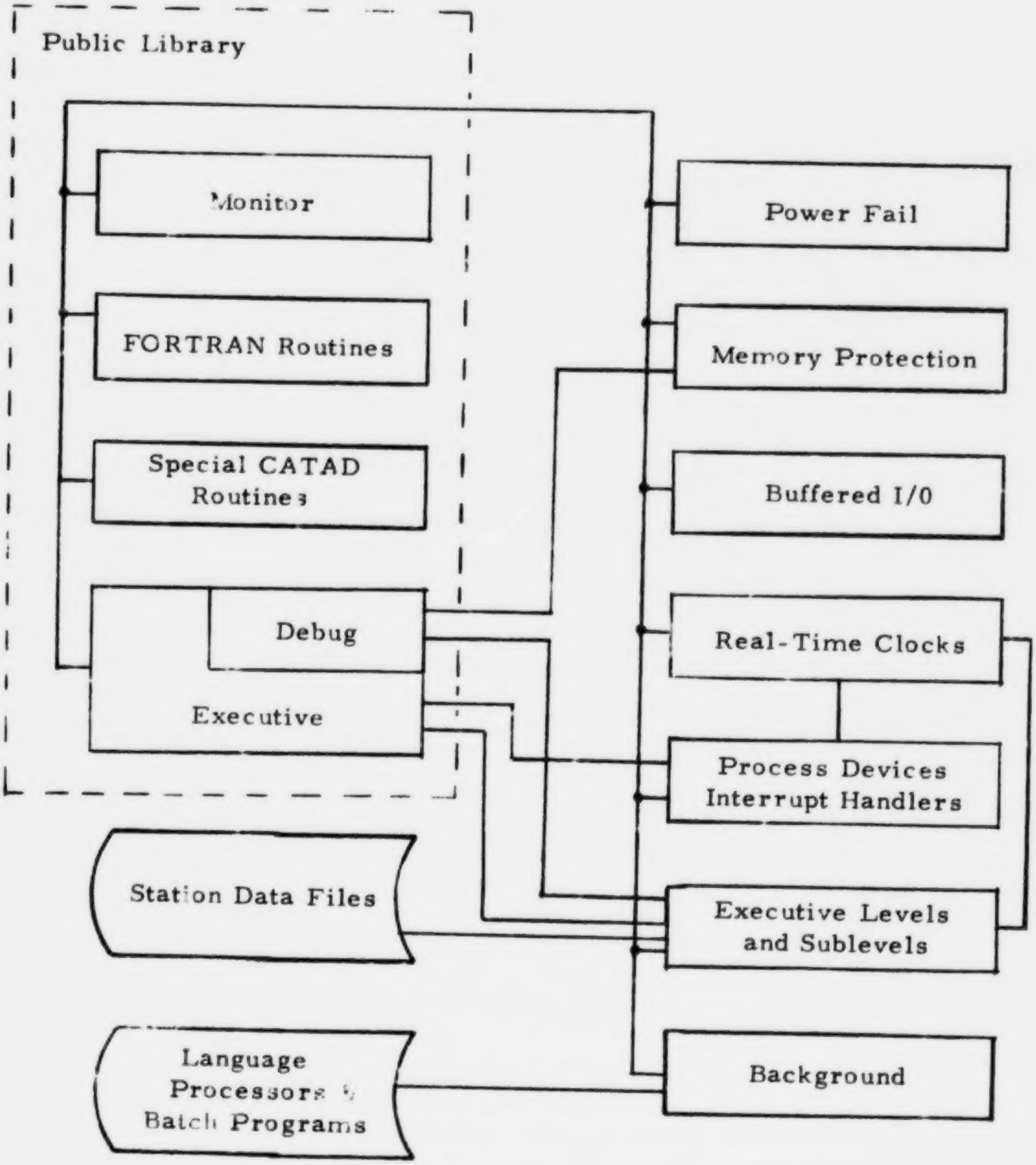

Public Library
Monitor
FORTRAN Routines
Special CATAD Routines
Debug
Executive
Station Data Files
Language Processors & Batch Programs
Power Fail
Memory Protection
Buffered I/0
Real-Time Clocks
Process Devices Interrupt Handlers
Executive Levels and Sublevels
Background

FIGURE 39

BLOCK DIAGRAM - CATAD SOFTWARE

Various CATAD program functions required significant operating system extensions. All extensions have been developed without altering the vendor-furnished software. Thus, future operating systems released by the vendor may be incorporated into the CATAD system without changing the revised operating system or reprogramming the extensions.

Operating System

The basic operating system used by the CATAD system computer is the supplier's real-time batch monitor (RBM). The operating system provided by the computer supplier provides the following system functions:

1. Multiprogramming
2. Public library subroutines
3. Background checkpoint/restart
4. Overlay loader
5. Disk management system
6. Peripheral device input and output
7. Accounting and elapsed-time routines
8. System initialization and creation
9. Real-time tasks
10. Control commands

Multiprogramming -- The operating system permits convenient execution of multiple foreground real-time control tasks and background job batch processing. Foreground tasks are protected during execution of undebugged background jobs by the system's memory-protection hardware, which prevents foreground area alteration or transfer of control by a background program to a foreground area unless specifically allowed.

Public Library Subroutines -- The system provides a public library of reentrant subroutines which may be used by both foreground and background jobs. Subroutine reentrancy permits a foreground and background task to be interrupted during execution of the subroutine by a higher-level task which may execute the same subroutine. The public library for the CATAD system includes most of the important Fortran subroutines, including floating point arithmetic subroutines.

Background Checkpoint/Restart -- The checkpoint/restart feature permits a background job to be interrupted during execution by a foreground task and stored on the disk. The background area is placed in a protected status and may be used by the foreground task. This feature is very important to the CATAD system, which requires the entire core memory allocated to background jobs for execution of the foreground real-time model task.

Overlay Loader -- The overlay loader permits a large disk-resident task to be segmented into a group of smaller subtasks which can fit into a limited amount of core memory. The segments are stored on the high-speed head-per-track disk system and can be loaded very quickly into core memory. Since the buffered input/output system is used for segment transfers from the disk, other tasks may be processed while the segment is being loaded.

Disk Management System -- The disk management system permits use of the disk system for storage of disk-resident programs and temporary and permanent data files. Files may be stored either as sequential or random-access files.

Peripheral Device Input and Output -- The peripheral device input and output routines provide the means for data transfers between the computer core memory and peripheral devices attached to the buffered input/output channel. All input and output to the computer system's standard peripheral devices utilize two operating system routines: M:READ and M:WRITE. These routines initiate data transfers which, once started, will continue to completion without further program intervention. During data transfers, foreground tasks at other interrupt levels or background jobs may be processed. The task initiating the data transfer may request an interrupt at the completion of the transfer, which will resume processing the initial task unless a higher-priority task is then processed.

Accounting and Elapsed-Time Routines -- Routines provide background job accounting and elapsed-time measurement. Starting a job, the routine logs the start time, user name and account number. The accumulated elapsed time is logged at the end of each activity. At job completion, the date and time, the total background job time, the time used by foreground tasks during the job and the accumulated idle time within the job are logged. The total background time for the job is recorded in the accounting file on the disk.

System Initialization and Creation -- A system generation routine provides the means for creating a system for a specific hardware configuration and system application. Many features of the operating system require dedicated core memory and are only included at the option of the user. The selection of optional features to be included in the operating system is made during system creation.

Real-time Tasks -- The operating system provides routines to implement special hardware features provided for real-time systems. Operating system routines are provided by the computer manufacturer to implement the following special hardware features:

1. Power on/off
2. Memory-protection violation
3. Memory parity error

Control Commands -- The operating system provides routines for processing computer operator commands which initiate loading and execution of programs.

Operating System Replacement Routines

Special routines were prepared as replacements for standard operating system routines furnished by the computer manufacturer. These replacement routines either corrected deficiencies in the standard routines available at the time or provided extended capability as required by the executive system and the foreground and debug systems. Replacement routines were prepared for the following operating system functions:

1. Power on/off
2. Memory-protection violation

Power On/Off -- The power on/off interrupt handlers are designed to perform these major functions during a power shutdown and restart sequence:

1. Halt and then restart all active input and output.

2. Save and restore all hardware register status and resume execution where left off.

Upon detection of an impending power loss, the power-off interrupt handler is initiated, and all register contents are saved for restart. A check of all input/output channels is made, any active channel is halted, and a wait loop is entered. A power-off receiver is then executed. It reads and stores the time for the external real-time clock.

When power returns, the power-on interrupt is triggered, and all interrupts are disarmed and disabled. Those interrupts having connected tasks are then armed, enabled and checked to see if they were active at the time of power loss. If the task was active, a special restore routine is connected to the interrupt and triggered. All input/output channels active at power loss are then set to end-action-pending and error status so that retries of the transfer can be initiated by the originating interrupt levels. The protection registers are then restored, and the power-on message is bid. After the power-on receiver is run, the protection-violation and parity-error interrupt levels are run to completion at the power-on interrupt level if either or both were active at power loss. The last of these routines to be run then exits from the power-on interrupt level. A counter is set and incremented by an internal clock to provide a delay before exiting for full system recovery.

The power-on receiver for the CATAD system is designed to reset the protection registers for foreground debug if required. It also triggers all interrupt levels where clock or I/O completion interrupts might have been lost in the power failure.

The clock time is read from the external real-time clock and stored and a bid is placed for a lower level program to take appropriate action depending on the duration of the power outage.

Memory-Protection Violation -- The memory-protection hardware causes a unique hardware interrupt any time an instruction in unprotected memory attempts to modify or transfer to protected memory or attempts to execute an input, output or control instruction. Background programs, and foreground programs using the foreground debug system, are executed in unprotected memory. The interrupt initiates a protection-violation task which determines whether the violation is for any of the following, permissible, purposes:

1. A valid request for input or output on buffered input/output channel using operating system routines.

2. A valid request for use of public library subroutines.

3. A valid request for direct input or output to a process or direct control instruction device by the foreground task executes under the debug system.

If the violation does not satisfy any of these criteria, the task causing the violation is aborted either by the interrupt handler itself or via the foreground debug system.

All requests for program segment overlays and data transfers to core storage are checked to ensure that they do not extend beyond prescribed limits.

All requests for input are checked to ensure that buffer limits fall within prescribed areas. Requests for public library subroutine execution are checked to ensure that program control will return to prescribed areas of core memory after completion.

Process Device Input and Output Interrupt Handling

Core-resident interrupt-handling routines are provided for each process input and/or output device as follows:

1. Remote station telemetry
2. Satellite terminals
3. Printers

4. Console push buttons
5. Water quality monitor
6. Watchdog timeout

Each of these devices is attached to the computer direct input/output channel, and all input and output to the devices is under program control. Each device interface is provided with a separate hardware interrupt to the computer. The device interface unit signals the computer when data is ready for input to the computer or when a data output transfer has been completed.

A fast response is necessary for devices which input data to the computer. Once the data transfer has been initiated by the computer, the transfer proceeds, one word or one byte at a time, until the transfer is complete. The computer must therefore accept each data word or byte before the next byte arrives and displaces the preceding word or byte. The transmission by remote station telemetry of a single message requires a minimum of 26 milliseconds, and of a single character from the satellite terminals, a minimum of 8.33 milliseconds. This precludes any processing of the data by the interrupt handler using a disk-resident routine because the maximum disk access time is about 34 milliseconds.

The interrupt handlers therefore store input data in a buffer and after data transfer is complete, initiate processing by an application.

Remote station telemetry -- The primary task of the remote station interrupt handler is to respond to interrupts generated by the central station telemetry interface upon either completion of the successful serialization of each word of data to be transmitted to a remote station or upon reception of a word of data from a remote station. In addition, error recovery procedures have been added to the handler. This allows multiple attempts (usually three) to obtain a successful transmission of data to or from a remote station without requiring intervention by the application program, which initiates all scan or contact output sequences and processes the results of remote station activities after data transfer completion.

A remote station activity will be terminated and restarted, if any retry attempts are to be permitted, when any of the following error conditions are detected:

1. 200-300 milliseconds have elapsed between interrupts generated by the central station telemetry interface during a scan or command sequence

2. A remote station other than the desired station has responded to the central station telemetry interface

3. Bad data has been received from the remote station.

When a successful scan or command has been completed, or no more attempts to achieve a successful scan or command can be allowed, the remote station is turned off and a program is initiated to process the results of the scan. If the unsuccessful operation was a command to place a remote station under local control, an emergency command sequence is used which comprises:

1. Attempt to turn on remote station

2. Start command sequence whether or not station acknowledges receipt of request

3. Transmit command to remote station.

Satellite Terminals -- Separate hardware interrupts for the West Point and Renton Satellite Terminals are used for processing both input from the terminals and output to the terminals. Input to the computer from the device interface is asychronous, an interrupt being generated upon the completion of each character transmission. Output from the computer to the device interface is synchronous, the interrupt being triggered internally by a routine initiated by the 2 kHz real-time clock.

The interrupt handler for each satellite terminal completely directs all input or output once it is initiated by the applications program. The applications program specifies the input buffer into which data is to be stored or the output buffer from which data is to be transmitted, and no further action is required by the applications program.

During transmission of a series of characters to a satellite terminal, after transferring each character to the device interface, the routine sets the 2 kHz clock to trigger the interrupt handler after a delay of between nine and twelve milliseconds. At this time the driver outputs the next character. When a response is expected from the remote terminal, the clock is set for a delay of 90 milliseconds, and the driver waits for an interrupt from the hardware indicating that a character has been received. If the character is not received from the hardware within 90 milliseconds, the clock triggers the terminal interrupt handler, and the driver terminates the transmission and signals an error condition to the executive program.

The interrupt handler provides three modes of operation; two for data output and one for data input. The "poll" provides the means for data input, causing transmission of specific information displayed on the CRT at the satellite terminal to the central station. The "erase/write" and "row address write" modes may be used for data transmission. The "erase/write" clears the screen and writes the message starting in the upper left corner of the screen. The "row address write" does not erase the screen, but writes the message on the screen starting with the first position on the indicated row.

Although the two satellite terminals comprise entirely different hardware configurations, the Renton Satellite Terminal, being programmable, has been made to emulate exactly the fixed logic of the West Point Terminal. Interrupt handlers for both satellite terminals utilize a common reentrant input and output control subroutine resident in the Public Library but with separate areas containing data and other information, including the hardware address of the device, the address of the data buffer and its size, an indication whether data is being transmitted or received, and whether the message is to be printed at the satellite terminal.

Printers -- A single hardware interrupt is provided from the device interface for the events and logging printer. The interrupt handler completely directs output of messages to both teletypes once the message has been stored in a buffer by an applications program. The applications program specifies the beginning of the buffer in which the message is stored and the number of words in the message (two characters per word). All further action is handled by the interrupt handler.

Console Push Buttons -- The interrupt handler for the console push buttons receives an interrupt from the operator's console each time a push button switch is closed. The handler reads the status of the two words defining the matrix and determines which switch was closed. (If more than one push button was depressed simultaneously, there is no response to the command.) The handler then requests execution of the appropriate applications program operating under the executive system.

Water Quality Monitor Interrupt Handler -- The water quality monitor interrupt handler accepts character input from the water quality monitoring system to the device interface on the computer input/output channel and places the characters in a core buffer. Each time the device interface receives a new character from the water quality monitoring system, it triggers the computer water quality interrupt and initiates the interrupt handler.

The interrupt handler reads the character from the device interface and stores it in a 40-word buffer. Checks are made to see if the buffer is full or if the last character was a carriage return. If either of these conditions is true, an applications program is bid to store the data record on a disk file.

Watchdog Timeout Interrupt Handler -- The watchdog timeout interrupt handler is initiated by detection of a malfunction in the operation of the direct input/output channel by the watchdog timeout hardware.

The task searches for the read or write direct instruction which caused the fault. When it locates the instruction, it encodes a message containing the location and effective address of the instruction and prints the following message on the computer operator's console:

```
DIO FAULT:  LOCN:XXXX EFAD:XXXX
```

Real-Time Clock Routines

Real-time clock routines utilize the hardware real-time clocks for initiating applications programs at designated intervals, for synchronous output to hardware devices and for batch processing elapsed-time accounting. The real-time clock routines are executed by the Counter = 0 interrupt-handling routines, which set the clock counters to trigger the Counter = 0 interrupt at multiples of the basic clock interval. The Counter = 0 interrupt-handler tasks and the intervals between execution are shown in Table 11.

Table 11. PROGRAM CLOCK FUNCTIONS

Clock	Function	Program Interval (milliseconds)
Clock 1	Operating system elapsed-time accounting	1000
Clock 2	Synchronous output to satellite terminals	3
Clock 3	Applications program real-time initiation	100
Clock 4	Unused (Counter = 0 interrupt level used for non-clock purposes)	----

Clock 1 -- is used by the basic operating system for date and time and for elapsed time measurement for background job accounting.

Clock 2 -- is used to trigger the satellite terminal interrupts for synchronous output and for timeout on asynchronous of characters to or from the device interface.

Clock 3 -- is used for initiating all clock dependent real-time programs, for monitoring output to various devices, and in the implementation of the program timeout feature of the watchdog hardware. Output to various devices is monitored by checking to determine whether a completion interrupt or an input request has been received within a prescribed time after issuance of the output command. The principal functions of Clock 3 are as follows:

1. Issues watchdog hardware control command
2. Remote station telemetry timeout
3. Printer timeout
4. Debug program timeout
5. Maintains 24-hour time-of-day clocks and initiates programs at one-second intervals.

Executive System

The executive system provides multiprogramming capability for applications programs and directs input or output operations by these programs. The executive program also includes facilities for on-line testing and debugging of applications programs. It comprises a group of reentrant subroutines which are callable by applications programs written in either assembly language or in FORTRAN. The executive system also performs functions in connection with the foreground debug system and a system for implementing the program hang-up detection feature of the watchdog timeout hardware.

Multiprogramming -- The executive system provides for concurrent execution of ten applications programs. Programs are processed in a priority sequence. The program at the highest level of priority will be processed first until it is completed or until it is suspended for an input or output operation.

A subpriority scheme is also provided in which 16 related or unrelated programs may be assigned to each main level of program priority. When more than one request ("bid") is present for execution of a program at a main level of priority, the program at the highest level will be executed first. The execution of a program at any level of main priority must be completed before any other program at that same level of priority can be executed, regardless of its priority level.

Two basic procedures are common in utilizing core storage for multiprogramming:

1. Dynamic relocation or loading a program at execution time into any area of core memory which is available at execution time.

2. Loading each task into a specific area of core memory assigned to that task.

The CATAD system utilizes the second procedure. The main levels of program priority are controlled by ten hardware priority interrupts provided for each main priority level of applications program (see Figure 40). Programs at each main level of priority are allocated a specific area of core storage for execution. The levels of subpriority of various application programs are under control of an executive routine.

The areas of core memory allocated to each main level of priority are contiguous, each level occupying an integral multiple of 256 words (one page). The first page for each level contains temporary storage and information used by the executive routines for execution of programs on that level. The other page or pages allocated to each level are used exclusively for execution of the programs assigned to that main level. The program may be loaded and overlayed by any number of segments in sequence or may load a subroutine and transfer to it for better utilization of the available core storage. The storage allocated to the main level of lowest priority includes the entire area of core allocated to background jobs. The memory page which contains the information used by the executive program for this priority level is contiguous with the area allocated to the next-highest level of priority. However, execution of a program at the lowest level requires the use of the operating system background checkpoint/restart feature.

The main levels of priority are numbered from 0 to 9 and sublevels are numbered from 0 to 15, with level 0, sublevel 0, having the highest priority.

Each main level of priority has associated with it a dedicated area in core for COMMON data storage. The COMMON area for each level is used for input-output buffers, transferring data between programs, saving data between runs of a program, etc. In addition, there are areas in COMMON which contain general information not limited to a specific level. A program may access any information in COMMON but may modify only a limited number of cells (limited by debug considerations) outside of its own area in COMMON.

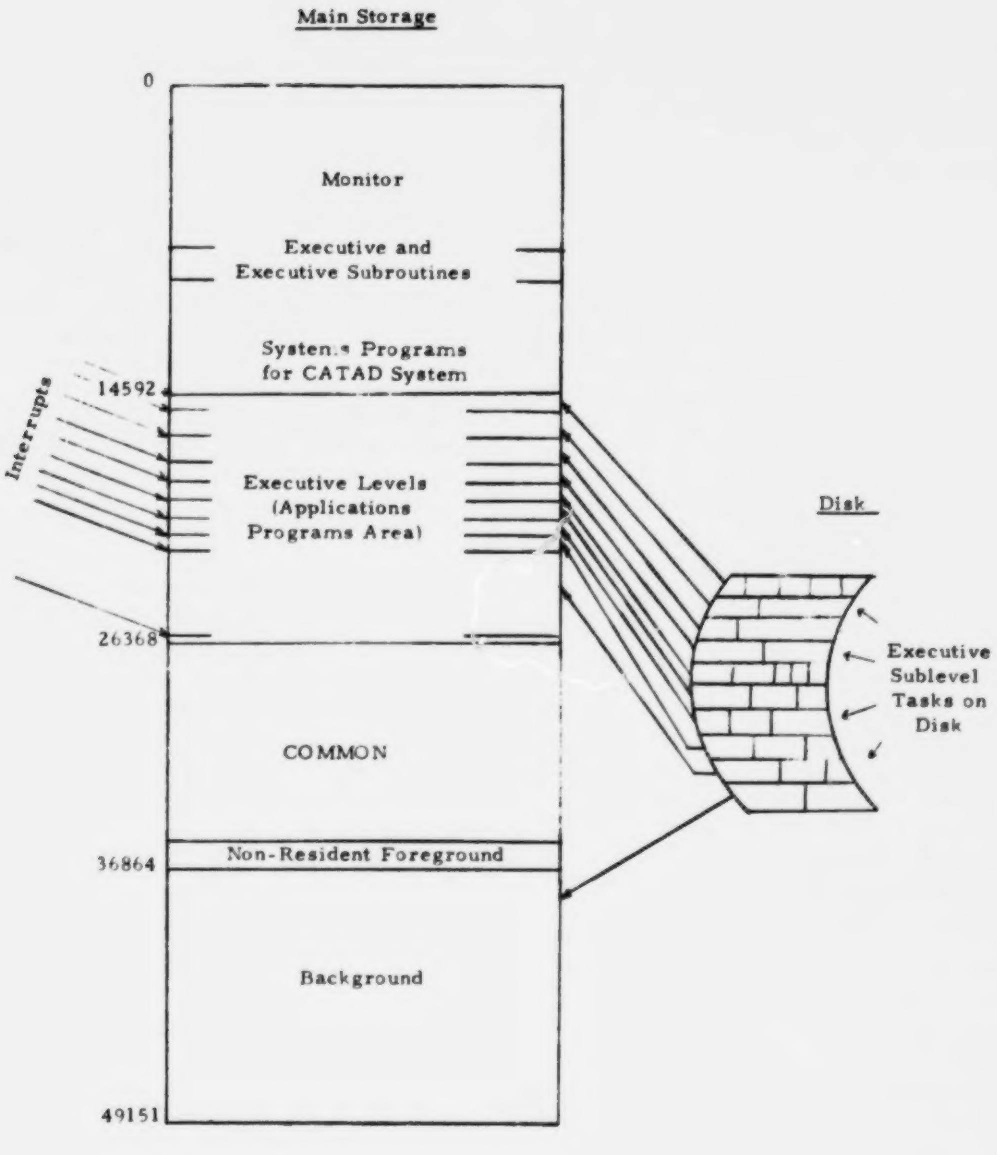

Main Storage
0
Monitor
Executive and
Executive Subroutines
Systems Programs
for CATAD System
14592
Interrupts
Executive Levels
(Applications
Programs Area)
26368
COMMON
Non-Resident Foreground
36864
Background
49151
Disk
Executive
Sublevel
Tasks on
Disk

FIGURE 40

CATAD EXECUTIVE STRUCTURE

Each applications program (which may perform multiple tasks) is assigned to a main level of priority and to a sublevel of priority within the main level. In order to execute an applications program, a bid is placed for that program either by calling the EX:SUBID subroutine in the executive giving the level and sublevel of the program, or by performing the necessary functions directly. The EX:SUBID subroutine can be called only by an application program which is executed within the executive. The EX:SUBID subroutine sets a bit corresponding to the program sublevel in a word associated with that level and triggers the hardware interrupt connected to that level. When that interrupt becomes the highest-level hardware interrupt waiting, the executive is entered and determines the highest-priority sublevel which has been bid and initiates the corresponding program. If the program has remained in core since last executed, no segment loading is required and control is transferred to the program immediately. Otherwise, the EX:LDSEG subroutine would be called on to load the appropriate program segment.

The EX:LDSEG subroutine, which may be called by any sublevel program as well as being used by the executive, loads the requested program segment using information generated by the operating system overlay loader. After the required program has been loaded into the program area, control is returned either to the sublevel which called EX:LDSEG or to the entry point for the program segment.

When execution of a sublevel program has been completed, it transfers to a routine EX:FINIS, which looks for any current bids at that sublevel; any such bids are handled in order or priority. If there are no bids pending, the program exits through the operating system routine M:EXIT, which performs the exit sequence and turns off the hardware interrupt.

Because each sublevel runs to completion when initiated, a long program could delay the processing of a high-priority program at another sublevel for an excessive period of time. To alleviate this program, the running program may bid for itself and exit. If a higher-priority sublevel at the same main level of priority is awaiting execution, it will be initiated. If no higher-priority sublevel has been requested, the program which was temporarily terminated will be resumed.

Direction of Input and Output -- Subroutines in the executive system direct input and output to foreground devices on the buffered input/output channel. Input or output subroutines are provided for the following devices by the executive system:

1. Fixed-head disk
2. Computer operator's console

3. Satellite terminals
4. Logging and events printers
5. CRT displays

The input and output subroutines perform the following functions:

1. Transform the given arguments from the calling sequence into the necessary form for the particular driver used

2. Check to see if the requested device is busy and queue or place the request next in line for execution if it is busy

3. Initiate the transfer by calling on the operating system service routine or interrupt handler associated with the device

4. Suspend the program requesting the input or output while in progress

5. Check the status upon completion of the input or output

6. Automatically retry most operations if the first try was unsuccessful

7. Print an error code if all tries are unsuccessful

8. Unsuspend and restart the sublevel which requested the input or output.

All calling sequences for input or output are compatible with programs written in FORTRAN. Programs written in assembly language use a FORTRAN-compatible calling sequence. The executive routine takes the arguments from this calling sequence and transforms them into the form required for the device by the operating system or by the interrupt handler.

To permit the maximum amount of processing while input or output functions are being performed, all requests for input or output operations are queued. Queuing allows better utilization of input/output devices and ensures the fastest possible response time for all foreground programs using a particular device. If a device is busy when input or output is first requested by an applications program, an indicator is set. When the current input or output operation is completed, the indicator is checked and the highest-priority program requesting the device is then activated.

After an applications program initiates an input or output operation via the executive subroutine or while waiting in a queue, the program is suspended and is resumed when the input or output operation is complete. Programs at a lower level of priority may be executed during the input or output operation, subject to interruption by a higher-priority task.

The executive input/output routines check each input or output operation upon completion and, if unsuccessful, the operation will usually be repeated a maximum of three times. If the operation is still unsuccessful, an error message will be printed on the computer operator's console. The error message indicates the time, level, sublevel and the location from which the input or output operation was requested, and a code indicating the type of error.

Fixed-head disk and CRT display-error messages are output each time a failure occurs because both are infrequent and because the disk is critical to system operation. Teletype and satellite terminal error messages, which are more common, are printed once and will be reprinted only after the failure has cleared and recurred.

A supplement to the checks made by the operating system has been found necessary when reading and writing data to the disk. Occasionally, a single byte will be lost when transferring data to or from the disk. This particular failure is detected by inserting a check word as the last word on each disk sector. A special routine verifies the check word after reading the data; and if the check word is not present, the bad sector is stored for later analysis, a message detailing the failure is printed on the computer operator's console, and the sector is restored from a backup disk file.

Additional system security is gained by having two teletypes for the logging functions. Normally one teletype is dedicated to alarm and events printing and the other to hourly logs, demand logs, and alarm review; but if one teletype should fail, all logging functions are sent to the other teletype automatically.

The following subroutine calls with arguments provide FORTRAN-compatible calls for input/output to foreground devices.

`EX:RADRD (FILE,BUFFER,WORDS,SECTOR)`

Reads the specified number of words into the buffer starting at the given sector of the disk file to which the operational label is assigned.

EX:RADWT (FILE, BUFFER, WORDS, SECTOR)

Writes the specified number of words from the buffer starting at the specified sector of the disk file.

EX:CHKRD (FILE, BUFFER, WORDS, SECTOR)

Reads the specified number of words into the buffer starting at the specified sector of the disk file. The last word is incorrect, the sector is saved, an error message is printed, and the sector is restored from a backup file specified in a table.

EX:MESSG (BUFFER, WORDS)

Writes the specified number of words of EBCDIC characters from the buffer to the keyboard printer.

EX:CRTWT (DEVICE, BUFFER, WORDS)

Writes the specified number of words of control and ASCII characters to the console logger teletype.

EX:WPTRD (BUFFER, SIZE, WORDS, STATUS)

EX:RTNRD (BUFFER, SIZE, WORDS, STATUS)

Reads characters input by the operator at the West Point or Renton Satellite Terminal and packs them two ASCII characters per word in the specified buffer. The number of words filled is returned with an error status number. If the number of words filled exceeds the buffer size specified, error status is returned. The status value details the type of error that occurred, with zero indicating a successful operation.

EX:WPTWT (BUFFER, WORDS, PRINT, MODE, STATUS)

EX:RTNWT (BUFFER, WORDS, PRINT, MODE, STATUS)

Outputs the specified number of words of ASCII characters from the specified buffer to the West Point or Renton Satellite Terminal and designates the transmit mode and whether output by the satellite terminal printer is requested. The status value details the type of error which occurred, with a zero indicating successful completion.

Program Hang-Up Detection

The executive system incorporates a procedure for detecting a program hang-up and implementing the program timeout feature of the watchdog timeout hardware (see Figure 41). The program timeout feature, if implemented, requires that a control command be issued to the watchdog hardware within a timeout interval of 1024 milliseconds. Failure to issue the control command within the prescribed interval causes closure of a relay which can be connected to the control circuits of an external device to activate or deactivate the device. In the CATAD system, the relay is connected to the remote station telemetry circuits in such a way that closure cuts off the signal carrier to remote stations, which transfers the stations to local control via carrier detection hardware.

To monitor the system for program hang-ups, the control command to the watchdog timer must be initiated by a program at the lowest level of priority. The watchdog program at a low priority level cannot initiate the control command if there is a hang-up in a program at a higher level which will not release control of the processor. Since the execution of a number of applications programs will require substantially more time than allowed by the hardware timer, a method was developed using software for effectively increasing the timeout interval to three minutes. The program hang-up detection scheme detects hang-ups at any level of priority above executive level eight. Executive levels eight and nine contain routines which may exceed the three-minute timeout.

Program hang-up detection is implemented via three related programs which are executed at three different hardware priority levels. Each program must be executed within a prescribed time interval.

1. A program at the highest sublevel of executive main level seven sets a core location used as a watchdog clock to -1800 and resets a watchdog indicator to 0.
2. A routine at the highest level and sublevel of priority in the executive system, which is initiated at one-second intervals by the real-time clock, sets a watchdog indicator and requests execution of the program at executive level seven at one-minute intervals.
3. A program initiated by a hardware interrupt which is triggered by the 60 hz real-time clock, checks the watchdog clock every 100 milliseconds and, if non-zero, increments the clock and issues a control command to

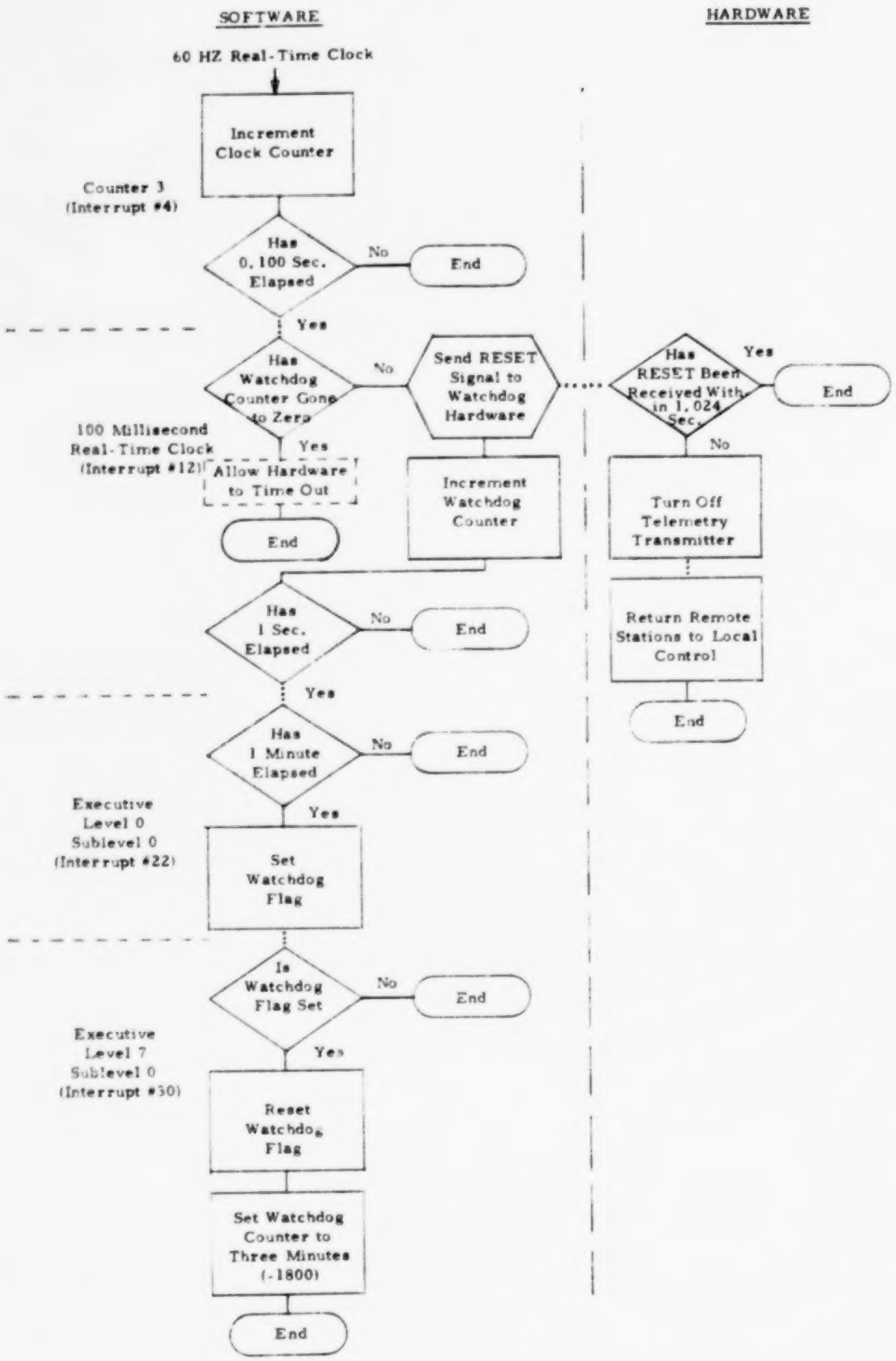

SOFTWARE
HARDWARE
60 HZ Real-Time Clock
Increment Clock Counter
Counter 3 (Interrupt #4)
Has 0.100 Sec. Elapsed
No
End
Yes
Has Watchdog Counter Gone to Zero
No
Send RESET Signal to Watchdog Hardware
Has RESET Been Received Within 1.024 Sec.
Yes
End
No
100 Millisecond Real-Time Clock (Interrupt #12)
Yes
Allow Hardware to Time Out
End
Increment Watchdog Counter
Turn Off Telemetry Transmitter
Return Remote Stations to Local Control
End
Has 1 Sec. Elapsed
No
End
Yes
Has 1 Minute Elapsed
No
End
Yes
Executive Level 0 Sublevel 0 (Interrupt #22)
Set Watchdog Flag
Is Watchdog Flag Set
No
End
Yes
Executive Level 7 Sublevel 0 (Interrupt #30)
Reset Watchdog Flag
Set Watchdog Counter to Three Minutes (-1800)
End

FIGURE 41

PROGRAM HANG-UP DETECTION FLOWCHART

the watchdog hardware. If the timer has decremented to zero, no command is issued, and the hardware will time-out, closing the relay.

Time out of the watchdog will, therefore, occur under any of the following conditions:

1. The 100-millisecond clock program does not run within the watchdog hardware time interval
2. The watchdog routine at executive level seven does not run within three minutes after requested by the watchdog routine at executive level zero
3. The watchdog routine at executive level zero does not request execution of the watchdog routine at executive level seven within three minutes of the previous request.

Foreground Debug

The foreground debug routines permit the testing and debugging of applications programs under real-time conditions while tested and proven features of the CATAD system continue in normal operation. The debug system is enabled by the hardware memory-protection feature of the computer which provides positive protection to designated areas of core memory without affecting the execution of programs in unprotected areas.

Because applications programs are executed under the executive system, the design of the debug system is closely related to the executive system, and components of the debug system are included therein.

The foreground debug system comprises routines which are incorporated into various parts of the system as follows:

1. Memory-protection violation task
2. Real-time clock routines
3. Public library routines
4. Executive system routines
5. Special non-resident debug routines

Memory-Protection Violation Task -- The memory-protection violation task is initiated when a program being executed in unprotected core memory attempts to modify or transfer control to a protected area of core memory or attempts to perform an input or output operation directly. The memory-protection violation task has been described previously.

In addition to the normal protection functions, the programmer may define a list of allowable direct control or direct input or output operations by the program being debugged so that a real-time program may be tested for correct input and output operation.

When a foreground applications program is being debugged, all core memory within the area allocated to programs at the main level of priority of the program being debugged and associated COMMON storage is unprotected. All the remaining core storage is protected, including the memory allocated to background. Background is protected to ensure that the program being debugged would not adversely affect either background or foreground programs. Therefore, any active background program is suspended and saved on the disk until the foreground debugging process is completed, at which time the background program is restored from the disk and allowed to continue. While the application program is being debugged, it is the only program running in an unprotected status.

Real-time Clock Routines -- Two elapsed-time clocks have been set up to limit the amount of time that the sublevel under debug can run continuously. One clock monitors the total elapsed time, including input/output, that the program being debugged runs. The other clock keeps track of the computation time exclusive of input/output, that the sublevel runs. If either clock times out, it generally indicates that a programming problem, such as an endless loop or a parity error, has resulted from an attempt to access unavailable core memory, which causes the machine fault interrupt task to abort the level.

Public Library Routines -- Three public library subroutines are provided for modifying a limited number of cells outside the unprotected program and COMMON areas. These subroutines set a word to a given value, set a bit within a given word, clear a bit within a given word, and test a bit within a given word. In addition to allowing modification within the unprotected program and COMMON areas for programs being debugged, these subroutines check the address of the word to be modified against five prescribed modification areas. The limits on these additional areas are set to encompass only those core memory locations which may be modified. Each of these routines uses an executive routine to check the return address of the subroutine and verify that the addressed word is within either the program COMMON area or one of the modification areas.

Executive System Routines -- Executive routines direct the execution of the applications program which is being debugged.

Executive routines make the following validity checks for foreground programs being executed under the debug system:

1. Check arguments of calls to public library or executive system subroutines for buffer limits outside of areas prescribed by debug parameters entered by programmer.
2. Check requests for transfer of disk files by the program against a list of allowable files.
3. Check running time of program against limits as follows: 30 seconds maximum excluding suspension for input or output, 3 minutes maximum total running time.
4. Check the location to which control will be transferred against prescribed limits after completion of a segment overlay.
5. Check the number of words to be output via an executive routine against prescribed limits.
6. Check requests for execution of a protected foreground program against a list of permitted requests.

Executive routines will abort a program being executed under the debug system if an error is detected, and will initiate an error message via an executive routine.

All requests by foreground programs for execution of another applications program are checked to ensure that the sublevel of the requested program has not been suspended under the debug system.

Special Non-Resident Debug Routines -- The debug system includes a number of special-purpose routines which are not included in the normal CATAD system, but are loaded on request in an area of core allocated to non-resident routines. These routines perform the following functions:

1. Set up parameters for programs to be executed under debug system, including (a) level and sublevel, (b) beginning and last addresses of program and associated COMMON areas, (c) allowable core memory modification areas, (d) allowable devices and disk files, (e) allowable control actions, (f) allowable program requests.
2. Activate and deactivate debug system.

3. Terminate debug mode and place program in normal mode.

4. Suspend program being debugged and deactivate debug system.

5. Provide for loading applications programs in the system while it is on-line.

6. Provide dump of program registers for program committing the last protection violation; i.e., the foregound program being debugged.

Programming Languages

The specification for the CATAD system required two language processors to be available on the central computer: a macro assembler to be used primarily for system programming and other real-time programming, including all real-time I/O, and a FORTRAN compiler used both for programming some of the real-time tasks as well as for background batch processing. Important features specified for the assembler were input/output pseudo instructions and the macro instruction capability. Features of the FORTRAN compiler required by the specification had to satisfy ANSI X3.9-1966, FORTRAN with a few exceptions to permit compilation of Metro's existing library of programs and the capability for interfacing assembly language with FORTRAN. Although the original FORTRAN system consisted of the manufacturer's standard "Basic FORTRAN" compiler with a specially developed preprocessor designed to meet the requirements of the specification, shortly after delivery of the system, an ANSI FORTRAN compiler became available.

The ANSI FORTRAN compiler can process in-line assembly language within a FORTRAN program, though the real-time control program does not presently use this capability. The interface in use between the two languages is the mechanism of subroutine calls to assembly language from FORTRAN, and vice versa. Several FORTRAN-callable assembly language subroutines have been placed in the public library, including FORTRAN math routines and routines to manipulate bits within a word, to convert codes, and to perform executive services.

Assembler -- Principal elements of the three-pass assembler are symbolic machine instructions, macros, and assembler directives. These elements are arranged in a hierarchy, with assembler directives being the most basic. The assembler directives permit both the generation of machine code for output and the description of macros to the assembler. Macros, in turn, are used by the assembler to specify machine instructions in symbolic form, which alone or nested in other macros provide the bulk of symbolic coding for the CATAD system. Among the special-purpose macros written to expedite programming for CATAD are macros describing an extended set of conditional branches and macros which allow text to be prepared in computer-compatible EBCDIC code but assembled in peripheral-compatible ASCII code.

The assembler frees the programmer from concern about addressing modes. For storage-addressing machine instructions or directives, the assembler automatically chooses the appropriate one of several machine-defined addressing techniques. Depending on the contents of the location counter, the base register and directives in effect, the assembler may invoke non-relative, self-relative, base-relative, or indirect addressing in the object code generated for a statement.

FORTRAN Compiler -- The use of FORTRAN in CATAD real-time programs is limited to subroutines which perform extensive floating point calculations on array variables: specifically flow, storage, and auto-control calculations in level eight and the model in level nine. The ANSI compatible compiler is a one-pass processor with an option for listing the output of a compilation in assembly language form and for conditioned compilation of designated FORTRAN source statements. All floating point calculations are performed in three-word extended precision. Integers occupy one word. The FORTRAN library loaded with FORTRAN programs contains subroutines defining arithmetic operations for floating point variables, as well as routines defining all the intrinsic and basic external functions of the language. All FORTRAN library subroutines used by real-time routines are reentrant and are permanently resident in the public library. This makes them available for use by both foreground and background programs; thus saving a considerable amount of core space.

Real-time FORTRAN programs do not communicate directly with station data files on the disk system, so they contain no FORTRAN input or output statements. Data is transferred to and from real-time FORTRAN programs either through argument lists or via the COMMON area, which is accessible for reference by both FORTRAN and assembly language programs and is accessible from all levels.

REAL-TIME APPLICATIONS PROGRAMS

All CATAD system real-time applications programs are executed in a multiprogrammed mode under the control of the executive system. The priority assignment of each applications program is shown in Appendix D.

Real-time programs are described here in terms of their functional application rather than by their priority assignment. Following is a list of principal functional applications:

1. Executive Clocks
2. Remote Station Telemetry Control
3. Contact Status Monitoring
4. Analog Data Monitoring
5. Alarm Processing
6. Data Storage Routines
7. Console Routines
8. Satellite Terminal Routines
9. Logging Routines
10. Hydraulic Calculations
11. Supervisory Control Routines
12. Automatic Control Strategy

Priority Assignment

Generally program priority has been assigned on the basis of urgency, time dependency, frequency of execution, logical sequencing of execution and program duration.

Tasks which relate to the security of the system, e.g., central station contact status monitoring, environmental protection system alarming, and remote station command control, are at the highest level of priority. Time dependent tasks, such as the executive system clock, telemetry system control and satellite terminal poll control, are at this same level.

Tasks which are performed frequently and at regular intervals, such as remote station data acquisition, are assigned higher levels of priority than tasks which are performed on a random basis such as console or satellite terminal operation.

The logical sequence of execution has also been considered in priority assignment. Thus, remote station data acquisition, remote station status monitoring, analog scaling, alarm processing and the hydraulic calculations which use these data are executed in decreasing order of priority.

Tasks which require the longest time for execution, such as hydraulic calculations and the real-time model, are executed at the lowest levels of priority.

Executive Clocks

Executive clocks initiate real-time tasks at prescribed intervals. Each executive clock consists of a core memory location which is incremented at one-second intervals when activated by an executive routine initiated by the real-time clock interrupt handler. A clock is activated by storing a negative integer at the core memory location. The clock will timeout, i.e., increment to zero, after the number of seconds specified by the integer number have elapsed.

Four executive system clocks are provided for each remote station which perform the following functions:

1. Initiate station periodic scans
2. Initiate station data scans after a time delay following a station control change command
3. Initiate station data scans during regulator gate position changes after program-controlled time delays
4. Initiate station data scans during setpoint changes at pump stations or regulator stations or during outfall gate position changes after program-controlled time delays.

The interval for periodic scans may be altered by the console operator either on a station-by-station basis or on a system (West Point or Renton) basis.

Executive clocks provided for each of the two satellite stations are used as time delay clocks in terminal control.

The executive routine also checks the minutes and seconds clocks and initiates the following tasks at the prescribed intervals shown below:

Function	Interval
Satellite terminal polling	10 sec.
Watchdog timeout program request	60 sec.
Hourly log data freeze	60 min. (on hour)
Water Quality log	60 min. (15 min. after hour)

The executive routine which is executed at one-second intervals also initiates the following tasks each second:

1. Monitor central station environmental system
2. Blink appropriate lamps on console and map display

Remote Station Computation Intervals

Remote stations are scanned at regular intervals. The intervals for data scanning and computation depend upon storm water flow conditions. Data at each remote station is scanned at primary interval and various computations are made at multiples of the primary interval.

At each primary interval, the following computations diagrammed on Figure 42 are made for each remote station:

1. The reference voltage is checked against limits
2. Readings of analog sensors are checked against sensor limits and out of limits conditions alarmed
3. Analog values are checked against control limits and alarmed if out of limits
4. Analog values are digitally filtered to dampen wave action or surges and eliminate electrical noise which has been superimposed on the signals
5. Status points are checked for change and if an abnormal condition exists, an alarm is output to an events printer

Secondary computations are made following the completion of every fifth data scan. The secondary interval computations which are diagrammed on Figure 43 include:

1. Computing flow through each regulator or outfall gate
2. Computing flow through each pumping station
3. Computing inflow to each regulator and pump station and upstream storage volumes
4. Checking storage volumes against operating rule curves and initiation of control action when required.

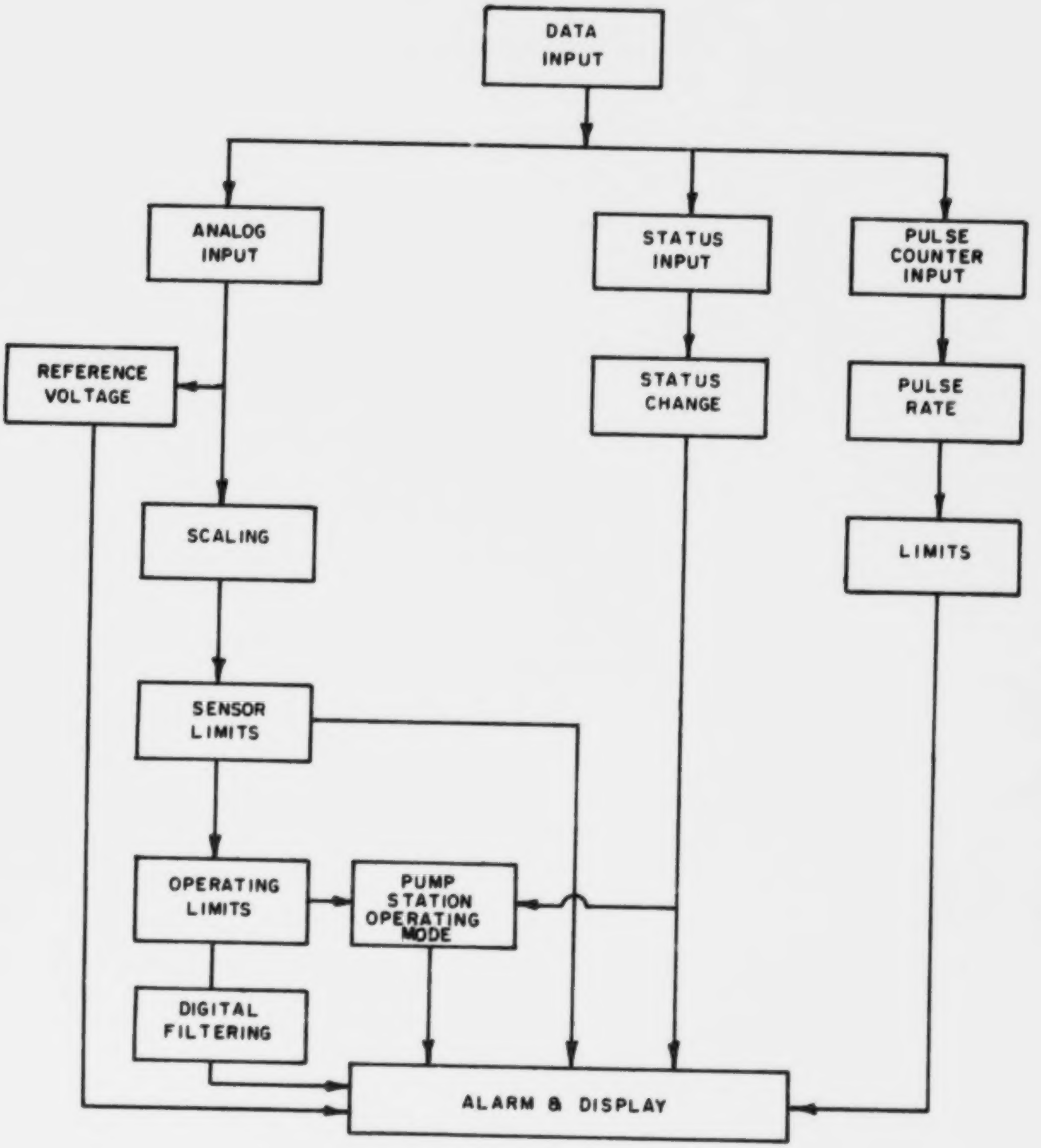

DATA INPUT
ANALOG INPUT
STATUS INPUT
PULSE COUNTER INPUT
REFERENCE VOLTAGE
STATUS CHANGE
PULSE RATE
SCALING
LIMITS
SENSOR LIMITS
OPERATING LIMITS
PUMP STATION OPERATING MODE
DIGITAL FILTERING
ALARM & DISPLAY

FIGURE 42

PRIMARY INTERVAL COMPUTATIONS

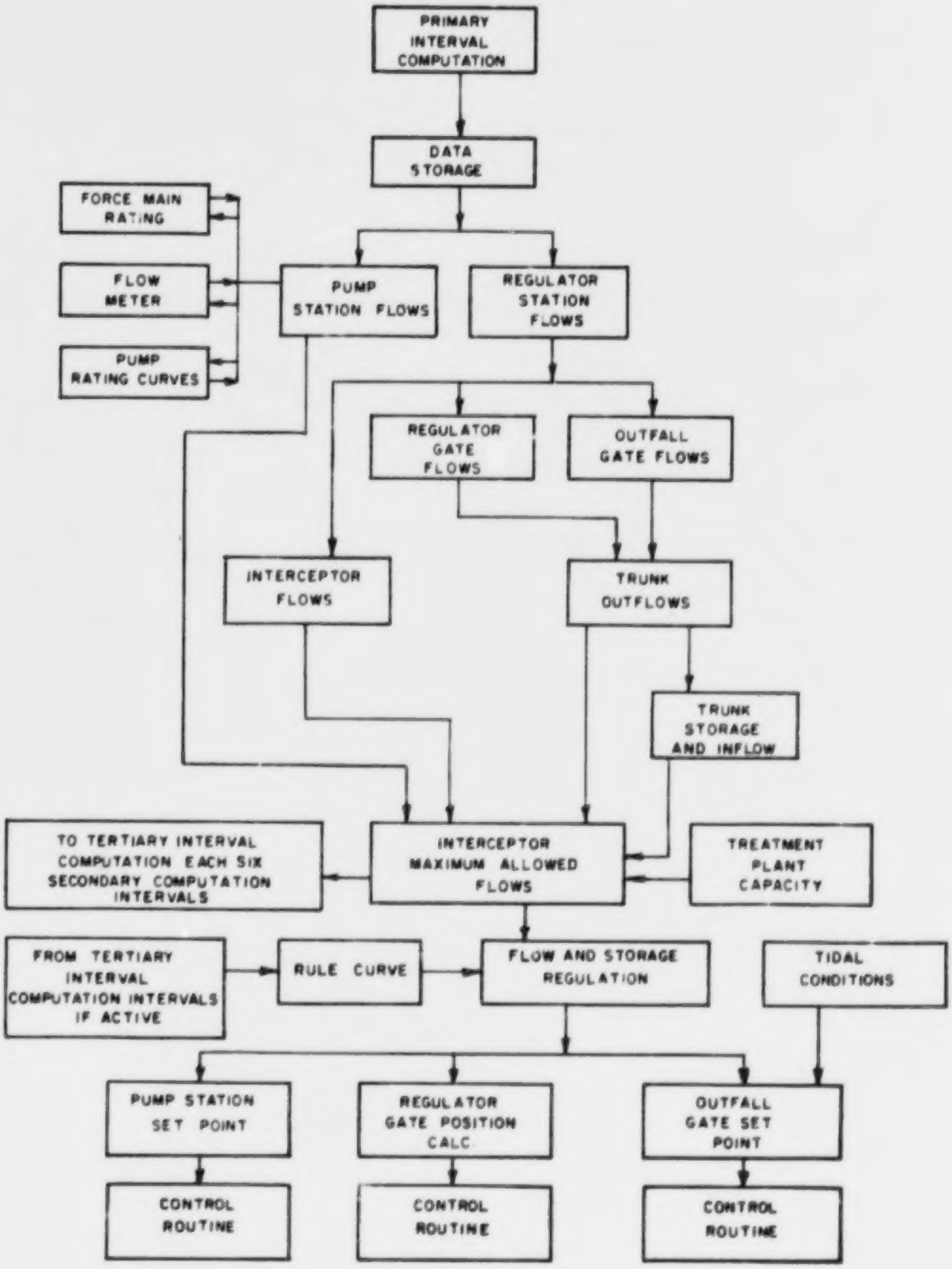

PRIMARY INTERVAL COMPUTATION
DATA STORAGE
FORCE MAIN RATING
FLOW METER
PUMP RATING CURVES
PUMP STATION FLOWS
REGULATOR STATION FLOWS
REGULATOR GATE FLOWS
OUTFALL GATE FLOWS
INTERCEPTOR FLOWS
TRUNK OUTFLOWS
TRUNK STORAGE AND INFLOW
TO TERTIARY INTERVAL COMPUTATION EACH SIX SECONDARY COMPUTATION INTERVALS
INTERCEPTOR MAXIMUM ALLOWED FLOWS
TREATMENT PLANT CAPACITY
FROM TERTIARY INTERVAL COMPUTATION INTERVALS IF ACTIVE
RULE CURVE
FLOW AND STORAGE REGULATION
TIDAL CONDITIONS
PUMP STATION SET POINT
REGULATOR GATE POSITION CALC.
OUTFALL GATE SET POINT
CONTROL ROUTINE
CONTROL ROUTINE
CONTROL ROUTINE

FIGURE 43

SECONDARY INTERVAL COMPUTATION MODULE

The tertiary interval computations comprise the detailed flow routing and storage regulation calculations diagrammed on Figure 44 to project inflow hydrographs at each remote station from measured rainfall amounts and adjust rule curves in accordance with the previously described procedure. Tertiary interval computations are made at six secondary intervals.

Remote Station Telemetry Control

Remote station data acquisition and control programs perform the following functions:

1. Remote station transmission initiation
2. Command starting
3. Command control
4. Telemetry data storage

Remote Station Transmission Initiation -- An executive routine which is a part of the same program as the executive clock routines initiates three types of remote station scans in strict order of priority as follows:

1. Contact change requests
2. Command scan requests
3. Periodic scan requests

All scan requests at each level of scan priority are completed before any requests at a lower level of priority are implemented.

Command Starting -- All commands to cause a change in control mode or to cause gate movements or setpoint changes are effected by opening or closing contacts at the remote stations. Changes in control station mode (e.g., from local to supervisory control), gate position and setpoint commands, whether originated externally by the operator or internally by a program within the executive system, are directed to the command and starter routine. It is important to channel all requests through this program to ensure that necessary validity checks are performed and to prevent interference between two commands at a station. Therefore, the routine checks commands for validity and schedules commands to be started in order of priority.

Before a command start request is processed, a check is made to ensure that there are no contact changes in progress at the station. A contact change is considered to be in progress from the time that it has been initiated by the command starter until it has been determined by the command scan handler that the change is either successful or incomplete. After either determination has been made, the command handler will request the command starter to check for additional command requests.

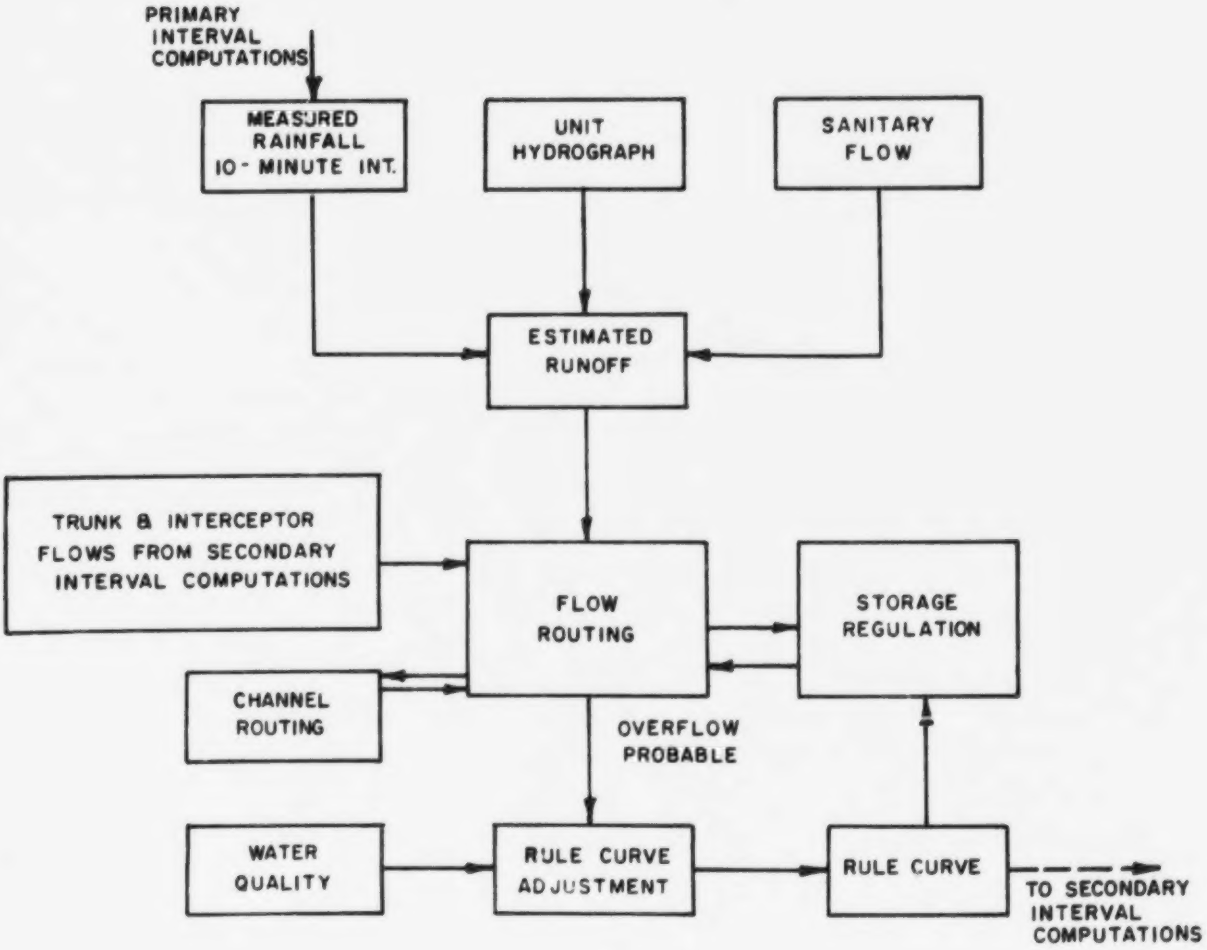

PRIMARY INTERVAL COMPUTATIONS
MEASURED RAINFALL 10-MINUTE INT.
UNIT HYDROGRAPH
SANITARY FLOW
ESTIMATED RUNOFF
TRUNK & INTERCEPTOR FLOWS FROM SECONDARY INTERVAL COMPUTATIONS
FLOW ROUTING
STORAGE REGULATION
CHANNEL ROUTING
OVERFLOW PROBABLE
WATER QUALITY
RULE CURVE ADJUSTMENT
RULE CURVE
TO SECONDARY INTERVAL COMPUTATIONS

FIGURE 44

TERTIARY INTERVAL COMPUTATION MODULES

The following command requests are valid:

1. Station control change (e.g., auto, supervisory or local control)
2. Outfall control change (for outfall only)
3. Regulator gate move request
4. Setpoint move request
5. Outfall gate move request

After a control mode change has been requested and transmitted, all gate or setpoint movements currently in progress are halted because only the command enabling contact data (local or remote) are transmitted to the remote station. This occurs even if the station is already in remote control and a new remote control command is requested.

The following conditions must be true before a gate or setpoint movement will be accepted and started:

1. No telemetry or reference voltage alarm may be in effect
2. No gate/setpoint sensor alarm may be in effect
3. Requested movement is more than the control deadband
4. Requested position is positive
5. Requested position is within limits
6. Gate or setpoint movement is not currently in progress.

If all the above conditions are satisfied, the command starter flags the remote station as having a contact change in progress, sets up the contact output bits for transmission to the remote station and requests the remote station telemetry control routine to transmit the command contacts. If the command cannot be started because all the conditions are not satisfied, a routine is requested to update displays and print appropriate messages.

Command Scan Handler -- When a remote station has been commanded to change from one control mode to another, or a gate position or setpoint change has been initiated, command scans are issued via the remote station telemetry control routine. The command scan handler verifies that the requested contact changes have been implemented and monitors the progress of the gate or setpoint movement.

If the contact change was requested to change a station control mode, indicators are set to cause any command in progress to be aborted, and the new station control state is stored with other station data.

If the contact change was unsuccessful, the command handler requests the station driver to try to repeat the contact change command a maximum of three times. Otherwise, the remote station telemetry control is requested to process any pending scan requests, and the command starter routine is requested to initiate any unprocessed command requests.

If the contact change command starts a gate or setpoint movement, checks are made to ensure that the correct relays have been set and the appropriate station executive clock is initialized to trigger a command scan at the time that the routine predicts that the gate or setpoint will reach 50 percent of the requested movement.

After completion of the command scan, the following checks are made:

1. Proper operation of remote station telemetry system
2. Proper operation of analog-to-digital converter
3. Proper operation of sensors
4. Proper position of control status contacts
5. Proper rate of movement of gate or setpoint against limits.

If any of these conditions are not satisfied, the command handler sets up a command to terminate the operation and requests the remote station telemetry control routine to issue the command and a "command not complete" alarm is initiated. If the gate position is within specified control deadband limits, the command is similarly terminated. If all the checked conditions are satisfied and the requested position is not within the deadband, the command is allowed to continue and a clock is initialized to trigger a command scan when the gate or setpoint is predicted to reach 50 percent of the remaining travel and the above procedure is repeated. If the command is to close a gate completely, the movement is allowed to continue until the torque limiter on the gate motor trips the gate close auxiliary relay.

Telemetry Data Storage -- Complete data from a remote station scan is stored in 24 core memory locations, each containing 10 bits of station data as follows:

Contact status -- 8 words
Pulse counts -- 4 words
Analog signals -- 12 words

After the remote station interrupt handler has received all 24 words or has tried three times and failed, the interrupt handler initiates an applications program, which stores the data in a station raw data file, or, if the scan was unsuccessful, initiates a station telemetry alarm.

Contact Status Monitoring

Contact status is monitored at the remote stations and at the central station by applications programs.

Remote Station Change Detection -- A routine at executive level one compares the current status of contacts at the station with the proper status. If an alarm is detected, the routine updates the alarm status table in the station data file, which is used by the alarm processor. The routine also indicates the proper status of lights on the console alarm and status panel.

Central Station Status Monitoring -- An applications program at executive level zero reads the status of central station contact inputs which monitor the central station environmental protection system, including the following:

1. Products of combustion detectors (8)
2. High-temperature relay
3. Halon system trouble
4. Fire indicating unit trouble
5. Six volt DC battery trouble.

Detection of a change in status initiates a request for an alarm program which is also at level zero. If the change is from a normal condition to an alarm condition, the alarm program initiates transmission of an alarm message to the central station alarm printer and to both satellite terminals.

Analog Data Monitoring

Analog data monitoring routines perform scaling, limit checking, and digital filtering of analog signals from remote stations.

Data Scaling and Limit Checking -- The analog to digital converter is checked by a routine at executive level zero which compares a transmitted reference voltage against prescribed limits.

Two other executive system routines at executive level one (one for regulator stations and one for pump stations) convert analog voltages to levels, pump speeds and gate positions and compare these against prescribed limits. A check of pump speeds, number of pumps running and pump station mode is made at another priority level. In the event that any of the analog sensors are outside of prescribed limits, or the pump operation does not check against programmed pump operation, the routines update the appropriate status word in the alarm status file in the station data file for the alarm processor. The routines also update the table in the station data file showing the proper status of lamps on the console alarm and events panel for use by the console routine.

The scaled values are stored on the converted station data file.

Digital Filtering -- Analog smoothing routines read the results of data scaling routines from the converted station data file; certain analog values are smoothed using a first degree regression on the five most recent values. The filtered analog values are used for hydraulic calculations and for display on the operator's console CRT displays and are stored on the station flow data file.

Pulse Monitoring

Pulse counters at remote stations record pulse counts from pulse generators and from rain gages. Each pulse counter is a 9-bit binary counter holding a maximum of 511 counts, rolling over to zero on the next count after the counter is full. Current and previous readings of the pulse counter routines determine the number of pulses received within a ten-minute interval, correcting for roll over if necessary.

An electrical spike or power failure may cause the pulse counter to reset to zero resulting in an erroneous reading. Such an occurrence can be detected by a reasonability check of the incoming pulse counts.

Pulse Generators -- Pulse generators are incorporated in the control circuits at a number of remote stations. The operation of these pulse counters is essential to the proper operation of the control system and they are monitored to detect any malfunction. The pulse rate is then compared with allowable limits, and if outside limits, the alarm status is stored in the alarm file in the station data file and in the light panel file in the station data files.

Rain Gage Monitoring -- There are currently six rain gages in use in the CATAD system. They are located at the East Marginal, Denny Lake Union, Matthews Park, Kenmore, Renton Treatment Plant and Kirkland remote stations. The rain gages are bucket-type which tip and dump whenever 0.01 inch of rain is collected. Each tip generates an electrical pulse which is accumulated in the pulse counter.

Rain gage pulse counts are transmitted from each station that has a rain gage whenever the station is scanned. After the scans are made at ten-minute increments past the hour, these readings are saved in computer memory. These data are subsequently accessed by a separate program task, checked for reasonableness and saved on disk files for use by both real-time and background tasks.

Each file record contains one station's rainfall for the 12 hours preceding the current time of day. The succeeding 12 hours are set to zero and may be used for predicted rainfall in projecting rainfall data. The file record is circular; thus the midnight reading is the 144th item on the list and the reading at time 0010 is the first item in the list. The rainfall readings are collected in real-time at ten-minute intervals throughout the day and saved in the file. Thus, the file will have a 12-hour history and space for 12 hours of projected rainfall whenever it is used.

Alarm Processing

The alarm processing routine is executed at executive level three and performs the following functions:

Alarm Count Checking -- To avoid excessively frequent alarm messages being logged, some alarms have to be repeated successively before an alarm message is output. An alarm counter file keeps the count of the number of successive recurrences of alarm conditions. If the count is less than a maximum, the alarm request is reset to normal; if the count is equal to or greater than the maximum count, however, the request is allowed to stand. The maximum count is generally one or two.

Alarm Status Change -- If an alarm status change is detected after the current alarm status has been processed by alarm count checking, whether from normal-to-alarm or a return-to-normal, an entry is made into the alarm table. Each entry in the table is three words long, comprising six items of data: the station number, an index to the alarm in the alarm message file, an indication of a return-to-normal or alarm message, the time of the alarm, the alarm value (if appropriate) and a decimal factor. This table provides enough information for the alarm printing programs to construct and print the message.

Alarm Message Output -- The alarm table provides the means for transmitting alarm messages to the satellite terminal alarm programs and the events logger alarm program. Within certain limits, each program can define alarm as required. Since a new alarm can be added to the table very rapidly, it is important to allow loggers time to print it without holding up further scans.

There are four pointers to the table:

1. The Renton Remote Terminal Index
2. The West Point Remote Terminal Index
3. The Events Logger Index
4. The Alarm Table Index

The Alarm Table Index points to the most recent entry to the table. The other pointers indicate the last entry processed by each logging program. If any one of the three alarm logging programs gets to be 30 entries behind, an alarm table overflow message is output to the satellite terminal or logger and the oldest alarm will not be transmitted to the device.

Data Storage

An efficient procedure for data base management is essential to real-time processing. The principal data files are as follows:

1. Station telemetered data
2. Station physical data
3. Station pipe data
4. Water quality data
5. Operating Data Storage
6. Rainfall data

Rainfall data files are discussed elsewhere in this report.

Station Data Storage -- Telemetered data from remote stations is stored on a new disk file after each step in processing. Although consuming more file space than a single data file, this procedure allows asynchronous processing of data from the same station at different levels of executive system priority.

If programs at different main levels within the executive system were simultaneously but independently processing data from the same station data file, the files would be located temporarily in separate areas of COMMON storage allocated to each level. If the program at each level processes a part of the data and sets up various indicators independent of the other programs, each program in storing its processed data back on the one disk file would write over and destroy the changes made by the other level. To avoid this, a rule has been set up so that two or more levels may not write to the same disk file.

The hierarchy of station files is as follows:

1. Raw data file -- contains raw station data from remote station telemetry
2. Converted data file -- contains scaled analog values, updated table of alarms and updated console lamp status
3. Flow data file -- same as 2 above with computed flows, storage amounts, further updated table of alarms and updated console lamp status
4. Alarm data file -- same as 3 above with pulse counter data, further updated table of alarms after modification by alarm counter and further updated console lamp status
5. Hourly log file -- same as 4, stored away each hour for the use of the hourly log program
6. Demand log file -- same as 4, stored away when a demand log is requested.

An alternative procedure (used by the contractor) required that each step in processing had to be completed before the next processing step was initiated. However, if one processing step requires substantially more computer processing time, this step becomes a bottleneck to computation.

Physical Data Files -- A physical data file for each station comprises station characteristics used in station hydraulic calculations as well as the results of these calculations. The contents of the physical data file are summarized on Table 12.

Pipe Data Files -- Pipe data files contain data on the storage element associated with each station as well as intermediate and final results of the storage calculation. The contents of the pipe data files are as follows:

1. Pipe data - dimension, slope and head loss coefficients
2. Storage rule curve data
3. Storage calculation - intermediate flow and level data
4. Calculated storage volumes.

Water Quality Data Storage -- An applications program initiated by the water quality interrupt handler takes and stores the contents of the core buffer filled by the handler on a disk file.

Table 12. CONTENTS OF PHYSICAL DATA FILES

Pump Stations

- Local station control program data
- Pump performance tables - head vs. discharge at constant speed
- Pump cavitation limits
- Head loss calculation data
- Force main calibration constants
- Bypass weir data
- Flow data - calculated and maximum
- Raw analog sensor historical data for digital filtering

Regulator Stations

- Geometric data - invert elevations
- Gate dimensions
- Gate coefficients
- Interceptor and return line piping data - dimensions, slope and head loss coefficients
- Bypass data - overflow weir or gate data
- Flow data - calculated and maximum
- Raw analog sensor historical data for digital filtering

Operating Data Storage -- An executive system routine stores station data files of selected remote stations or the entire system on magnetic tape files for use in background analysis or system operation. Storage of operating data is initiated or terminated from the computer operator's console rather than the system operator's console since this is essentially a background oriented task and requires demounting and mounting of magnetic tape reels.

Console Routines

All operator's console and map display board command and display functions are implemented under program control of the computer.

1. Lamp blinking
2. Console Control
3. Alarm and Status Display
4. CRT Display formatting

5. Station push button handler
6. Command push button handler
7. Segment push button handler
8. Digital data entry

One hundred and fifty push buttons, about 200 lights and 7 CRT screens form the operator's console. From the computer's standpoint, all push buttons differ only in that they have different hardware addresses. Programs are therefore necessary to differentiate between different types of push buttons and to initiate the appropriate operation. Decoding of push button switch closures is done by a core-resident hardware interrupt handler which initiates the appropriate push button processor.

In addition to processing push button requests, programs are needed to write CRT formats, update display data, and initiate control commands. Checks must be made to ensure that the operator observes specified rules in initiating commands. A number of miscellaneous tasks are required to process push button requests, turning on or off appropriate lamps, changing displays and printing messages.

Lamp Blinking -- Lamps on the operator's console and map display blink (one second on; one second off) to indicate the occurrence of an unacknowledged alarm or to designate on the map display the station last selected on the station select panels to which a supervisory command would be being transmitted. The lamps are blinked by a routine executed once each second which turns on or off the lamps for which a blink request has been made by the alarm processor or the station select push button handler. Blink requests are made for:

1. Station push buttons when an alarm occurs at the station until the station push button is depressed by the operator

2. Segment push button lower lamp (red cover) when an alarm occurs at a station within the segment until the push button is depressed

3. Alarm acknowledge push button when alarm occurs until the push button has been depressed

4. Map display station symbol red segment when alarm occurs at station until corresponding station select push button on the operator's console is depressed

5. Map display station symbol white segment when corresponding station select push button on the operator's console is depressed.

Console Control Panel -- The console control panel comprises the following items:

1. Digital data entry push buttons
2. Numeric projection-type display
3. "Invalid Command" indicating lamp
4. Push buttons as follows:
    - Lamp Test
    - Map Display Lamp Test
    - Console Power
    - Alarm Acknowledge
    - Cancel Entry
    - Enter

Following entry of any command the program checks the command for a valid entry sequence and input data limits. If the command does not satisfy the program requirements, the program turns on the "Invalid Command" lamp. If the command is acceptable it is printed on the events printer. The operator may check the printed command against his intended command and either press the "Enter" button to activate the command or the "Cancel Entry" push button to abort the request.

The "alarm acknowledge" push button blinks when a new alarm is detected. Depressing the push button turns off the lamp and the audible alarm.

The lamp test push button (and lamp test push button on each panel) and the console power push buttons are the only non-program controlled push buttons on the console.

Alarm and Status Display -- Alarm and status indications appear on both the map display and console panels. The following alarm indications appear continuously on either the console or map display.

1. The bottom lamp of the segment selection push button (red) is turned on

2. The red quadrant lamp of the station symbol on the map display is turned on for any alarm

3. The amber quadrant lamp of the station symbol on the map display is turned on for a high water level alarm.

The green quadrant lamp of the station symbol is turned on when the station is in either of the two remote control modes (supervisory mode or automatic mode).

The alarm and status panel on the console is a selectable display. Indicating lamps on the alarm and status panel display the current status at the station selected when the last station push button was depressed.

The status of all alarm and status lamps on the console and map display is updated after each station scan.

CRT Displays -- The seven console CRT units display alphanumeric data from a maximum seven of remote stations under computer control. The Metro interceptor system has been broken down into segments based on geographic and hydraulic considerations and data from remote stations within each segment are displayed simultaneously. The operator selects a particular segment for display on CRT units by depressing the appropriate segment select push button. The CRT displays are related to the map display by turning on a lamp within the map display symbols for the remote stations included in the current CRT display.

The CRT displays have a maximum capacity of 768 characters in 24 rows of 32 characters per row. The display capacity is not sufficient to display all data from each station so that the operator can select from any of three data groups for the CRT display (see Table 13).

Table 13. CATHODE RAY TUBE DISPLAYS

Mode	Display Type	Data
0	Hydraulic	Water levels Gate positions Pump speeds Flows Storage rates and volumes
1	Alarm	Current station alarms
2	Miscellaneous Data	Rainfall Overflow rate Pulse generator rate Explosion hazard levels

The display controller provides capabilities for blinking individual characters in the display. The blink feature is used in the hydraulic data display to indicate sensor values or computed values which are in an alarm status. Examples of the different display modes are shown in Figures 30, 31 and 32.

The display mode is controlled by a console command sequence in which the mode is entered via the digital data entry panel. Additional data formats may be added conveniently by the programmer.

The display formats are stored on disk files. To write the formats on the display, all seven screens are erased simultaneously and then filled with appropriate formats for the stations in the segment most recently selected. The formats are only written when a new segment is selected or the display mode is changed. Outputs to the displays which are attached to the computer buffered input/output channel are made via an operating system routine which initiates the data transfer from a core memory buffer to each display which is performed by the channel controller without further program action. An interrupt signals completion of the output to the display.

The CRT displays are updated after each station data scan.

Station Push Button Handler -- The station push button handler actually performs or initiates the following functions when triggered by the push button interrupt handler after the operator depresses a push button on the station panel other than a system push button.

1. Turns off the push button lamp previously on in the same station panel
2. Turns on the lamp in the depressed push button
3. Causes the alarm and events panel to display the status of the station associated with the push button
4. Terminates blinking of the push button lamp if blinking
5. Turns on white lamp of map display station symbol and sets up blink request
6. Initiates update of CRT displays and status and alarm panels.

Segment Select Push Button Handler -- The segment select push button handler actually performs or initiates the following functions when triggered by the push button interrupt handler after the operator depresses a push button on the segment select panel.

1. Turns off the upper push button lamp (white) previously on in the segment select panel
2. Turns on the upper push button lamp in the depressed push button
3. Terminates blinking of the lower push button lamp if blinking
4. Causes data for the stations within the segment to be displayed on the seven CRT displays in the current format mode
5. Turns off white lamps in map display which are on (except lamp that turned on by station select push button)
6. Turns on white lamp in map display in symbols for stations within the segment selected.

Command Push Button Handler -- The command push button handler actually performs or initiates the following functions when triggered by the push button interrupt handler after the operator has depressed a push button on the command panel.

1. Turns on the lamp in the push button which was depressed
2. Checks the entered command for validity, and if valid initiates printing of the command (where applicable) and if invalid turns on the "invalid command."

A tabulation of the type of checks made for each command is shown on Table 14.

Digital Data Entry Push Button Handler -- The digital data entry push button handler routine reads the push button which was depressed and causes the appropriate number to be displayed on the adjacent numerical display. As each digit is entered, the numbers in the display are shifted one position to the left. The digital data entry processor saves up to six consecutively entered digits, and keeps a running sum of the digits entered, assuming that the digits form a decimal number. If seven digits are entered consecutively, the "invalid command" light is turned on and the console is locked out by program until the cancel entry button is depressed.

Table 14. CONSOLE COMMAND CHECKS

Command Push Button	Valid Command for Station Type	Valid Command for System	Segment Containing Station Currently Displayed	Digital Data Entry Within Limits
Auto Control			x	x
Supervisory Control			x	x
Local Control		x		x
Regulator Gate Position	x		x	x
Outfall Gate Position	x		x	x
Setpoint Position	x		x	x
Diverted Flow	x		x	x
Maximum Flow	x			x
Pump Discharge	x		x	x
Alarm Review		x		
Demand Scan		x		
Data Log		x		
Rule Curve Duration				x
System Time				x
Scan Interval		x		x
Pump Sequence	x			x
Test				x

Satellite Terminal Routines

The satellite terminal applications programs were written to provide the operators at the treatment plants with the following capabilities:

1. Receiving system alarms
2. Monitoring remote station data and status
3. Placing a selected station or system into the local control mode from either the supervisory or automatic control modes
4. Entering treatment plant data for real-time control and for producing reports.

The seven programs, which access the two satellite terminals, run under two dedicated levels of the executive. The programs perform the following functions:

1. Poll the satellite terminal periodically to see if the operator has entered a request. If a request is present, this program will decode the request and bid for the correct program to handle the request.

2. Put a designated station or system into the local control mode

3. Send all alarm and normal messages to the satellite terminal

4. Display at the satellite terminal a summary of all alarm conditions at a specified station or system

5. Format and send to the satellite terminal a display of the data pertaining to a specified station

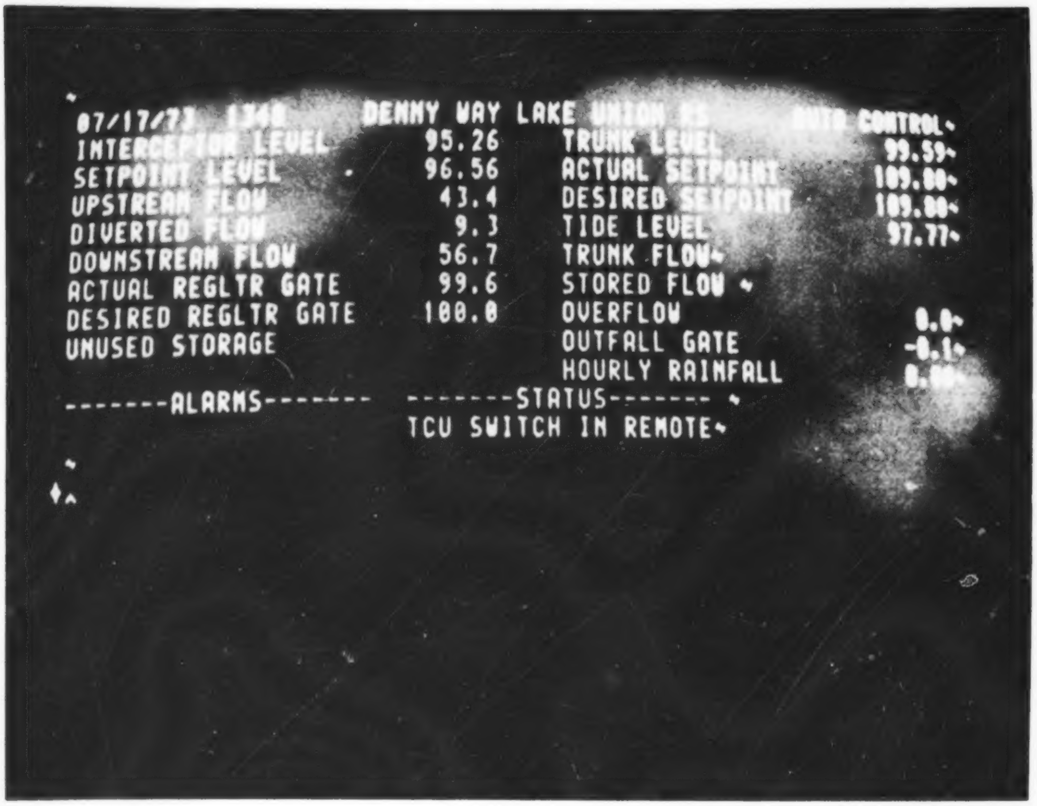
6. Allow the operator to enter digital data which can be used to generate reports on treatment plant operation. This program is also used to enter real-time operating data.

7. Sequence through various tests to check the functions of the satellite terminal.

The programs were originally prepared for the West Point Satellite Terminal. However, since the Renton Satellite Terminal emulates the West Point Terminal, the same programs can be used with only very minor differences. These differences result from the physical differences in screen sizes - the West Point display screen is arranged as 24 rows by 64 characters and the Renton display screen is arranged as 22 rows by 92 characters. Figure 45 shows a typical West Point console display.

Terminal Polling -- This routine is initiated every ten seconds by the executive clock. If another routine on this level is not in an uninterruptible condition, the program will immediately poll the satellite terminal. If the terminal operator has not entered a data transmission request and the time in minutes has changed, the date and time will be transmitted to the remote terminal and, on the hour, it will also be printed. If only the "ENTER" button at the remote terminal has been pushed (distinct in that the word count is zero), the poll program sends an "ENTER COMMAND" message to the remote terminal. Indicators are set so that no other program will output to the remote terminal for 30 seconds which will give the operator time to enter a command.

If the operator has entered a command, the program will read the command, decode it, check its validity, set flags and bid for the program which will perform the requested command. If the entered command is invalid, a message will be sent to the operator informing him of his error and requesting that he reenter the command.



```
07/17/73  1340     DENNY WAY LAKE UNION RS          AUTO CONTROL
INTERCEPTOR LEVEL          95.26    TRUNK LEVEL              99.59
SETPOINT LEVEL             96.56    ACTUAL SETPOINT         109.00
UPSTREAM FLOW              43.4     DESIRED SETPOINT        109.00
DIVERTED FLOW               9.3     TIDE LEVEL               97.77
DOWNSTREAM FLOW            56.7     TRUNK FLOW
ACTUAL REGLTR GATE         99.6     STORED FLOW
DESIRED REGLTR GATE       100.0     OVERFLOW                   0.0
UNUSED STORAGE                      OUTFALL GATE              -0.1
                                    HOURLY RAINFALL           0.00
-------ALARMS-------   -------STATUS------
                       TCU SWITCH IN REMOTE
```

FIGURE 45

WEST POINT CONSOLE DISPLAY

Control Command -- The control command routine permits the operators at the treatment plants, which are manned 24 hours, to restore a station or system of stations to local control. This operation might be performed when the central console is unmanned and a malfunction occurs at stations in automatic or supervisory mode.

To put a single station in local mode, the following command is entered by the operator: LOCAL, STATION, station name (minimum of four alphanumeric characters). (Underlined characters are required; others are optional.) To put an entire system in the local mode, the command would be: LOCAL, SYSTEM, system name (minimum of four characters). The poll routine, when it decodes the local command, indicates each station which is to be put in local mode and a request is then placed for the control program.

The control program echoes the command for verification by the operator before it issues the command. If the operator verifies the command, then the appropriate indicators are set and a request is placed for the command program to put the station in local control. A local control message is printed at the satellite terminal and on the events printer.

Alarm Routines -- The alarm routine is bid whenever any alarm or return-to-normal messages are entered into the alarm table. Each new alarm table entry is decoded and a complete message constructed. The message is then transmitted to the remote terminal where it is displayed and printed. If the status from sending the message is bad, it is resent, up to a fixed number of times, until the status is good. If the status is still bad after all retries have been made, a message is printed on the events logger indicating that the alarm message could not be sent to the remote terminal. After each alarm message is sent, a bid is made for the poll program (so the operator can enter a command) and this program. Rebidding for the alarm program allows for several alarm messages to be output in sequence without completely tying up the level.

Alarm Review -- The alarm review program allows the operator at the satellite terminal to request a display on the CRT and optionally print a review of all current alarms at a specific station or within an entire system. The commands used to initiate this display are:

ALARM REVIEW, STATION, station name, PRINT (optional) or

ALARM REVIEW, SYSTEM, system name, PRINT (optional)

The poll routine decodes these commands, sets requests for the station, or stations, for which an alarm review is desired and initiates the alarm review program.

The alarm review program sends out a heading including date and time and searches for a station with a request for an alarm review. The table of alarms in the station alarm data file is analyzed to see if any conditions are currently in alarm and if no alarms are present, the program continues on to the next station. If alarms are present, a message is constructed comprising the station name, the time of the last scan, and a list of current alarms. The alarm review program sets a request for its own execution and when reinitiated processes requests for alarm reviews for other stations.

Station Data Display -- The station data display program provides the operator at the satellite terminal with the ability to monitor field data at any pump or regulator station. The data displayed are the same as the hydraulic data displayed on the console CRT. In addition, explosion hazard, hourly rainfall data, and lines showing current station alarm and status are included in the same display.

To display the data from a specific station, or to display the data from all stations in an entire system sequentially, the operator enters the command:

DISPLAY, STATION, station name, PRINT (optional) or

DISPLAY, SYSTEM, system name, PRINT (optional).

The PRINT command optionally requests that the displayed data also be printed. The poll program decodes the command, sets indicators for the station or stations to be displayed and requests execution of the display program.

The display program checks each remote station until it finds a request for a display. It then reads the appropriate display format and the station data file from the disk. Data values are converted to ASCII format and placed in the display format. If any of the display values are in an alarm status, they are set off by brackets. The display characters are then packed, removing extra blanks, and transmitted to the satellite terminal. An additional line including explosion hazard and hourly rainfall is created and transmitted. Additional programs create tables of current alarms and status at that station and transmit the alarms to the remote terminal to appear at the bottom of the display. If there is a request for the display to be printed, it is coded into the last message sent. When the display of the current station is finished, the display program sets a request for its own execution and when reinitiated processes requests for displays at other stations. If there are no further requests, the program exits.

Data Entry -- The data entry program enables the satellite terminal operator to enter real-time data for use in control and to enter treatment plant data which can be used to generate daily reports. The format of the data entry command is

DATA, xx

where xx is a two-letter code which indicates to the program what type of data is to be entered. When the poll program decodes this command, the data entry program is requested.

The data entry program verifies that the given two-letter code is allowed, and, if allowable, acquires information regarding the data to be entered from a disk file corresponding to the given code. The information includes the number of data items to be entered, the locations in which the data are to be stored, the minimum and maximum value for each item of datum, and a string of characters describing each item. The item description is transmitted to the remote terminal where the operator enters the corresponding value and initiates transmission to the central station. The value received at the central station is decoded, checked for entry errors and echoed for verification. If the value is verified by the operator, it is checked against the given limits and if the value is within limits, it is stored in computer main or secondary storage. The program is repeated for each item of data until all data in the sequence have been entered.

Test Routine -- This program executes a series of tests or a single test designed to check the operation of the satellite terminal and its interface with the central computer. The format of the test command is:

```
TEST, n
```

where "n" is the number of the desired test function as described below:

0 (or no "n" given) - perform all test in sequence
1 - send full screen with bit pattern 01010101 (*'s)
2 - send full screen with bit pattern 10101010 (U's)
3 - send full screen of vertical bars (bit pattern 0111 1110)
4 - send full screen of dashes (bit pattern 00101101)
5 - perform comprehensive test.

Tests 1 and 2 are designed to check the computer linkage to the terminal. Tests 3 and 4 check the vertical and horizontal linearity of the display. Test 5 checks nearly all functions of the device and involves transmitting and receiving the full character set, comparing the transmitted and received characters and printing the full character set to check the operation of the hard copy printer. Test number 0 will perform tests 1 through 5 in sequence with a ten-second delay between each test.

Logging Routines

These programs execute all logging functions and most events messages printed on the logging and events printers. The only messages which are not output by the logging programs are command messages and certain system malfunction alarms. The logging routines construct and print the following messages.

1. LOGRALRM prints alarm and return-to-normal messages as they occur
2. LOGRHOUR prints an hourly log of all stations in each system
3. LOGRHADL prints a summary of any storm activity in the last hour
4. LOGRDMND prints a log of the current values at a given station or in a given system at the operators request
5. LOGRDADL prints a summary of storm activity since the beginning of the hour at a given station or in a given system at the operator's request
6. LOGRALRV prints a summary of all active alarms at a station or in a system depending on the request
7. LOGRWQAL (LOGRWQHD) prints the data acquired through the water quality monitoring equipment.

To allow the highest priority logging programs to run as soon as possible, each logging program except the alarm message program exits after printing one or two lines and requests its own execution, thereby permitting requested higher priority routines to be executed before completing the remainder of the log.

LOGRALRM - Alarm Logging -- This program formats and prints the alarm and normal messages on the events logger as they occur.

The alarm message is built up from the information in the alarm table to include an alarm or normal indication, the time the event occurred, the station name, a standard alarm message which indicates the priority of the alarm and for a sensor alarm the converted analog value. After the complete message is constructed, it is printed on the events printer. The program prints alarms until all messages in the alarm table have been printed.

LOGRHOUR - Hourly Log -- On the hour, the program which last updates the station data file stores a duplicate of the data on another file which remains frozen throughout the hour. When data for all stations have been frozen, a request is placed for each station and the hourly log program is bid. The hourly log program accesses the data so that the printed log shows data for all stations from the same scan. If for some reason the data for a station does not correspond to the time of the log, for example, if the telemetry has failed, the time of the last successful scan is printed on the log. A sample hourly log is shown in Figure 46.

```
06/16/73  0200  W POINT SYS   HOURLY LOG - REGULATOR STATION
               TRBLVL  TRBSET     TIDE   OUTPOS  OVRFLO  TRBFLO  STOFLO  UNUSTO
               INTLVL  INTSET            RECPOS  DIVFLO  UPSFLO  DNSFLO  BYPHAZ
DEXTER RS
               136.90  143.30
               135.09  137.75                       0.0    10.0    -1.1    0.18
                                          26.7     11.1            11.1     4.0
I CITY RS
               150.30  157.06
               113.87                               0.0
                                         100.0      6.4            26.5
UPR DENNY RS
               101.57  109.96   107.68    -0.1      0.0
                94.64   96.56             99.9     13.5    20.0    36.3
LOW DENNY RS
               100.93
                        96.56              0.3      0.0     4.5     0.0    0.04
                                          99.9      4.5
KING RS
               105.15           104.30    -0.1      0.0     4.6    -0.3    0.02
                97.76  102.40             46.4      4.9    22.2    27.1     5.0
CONN RS
               102.01  105.96   102.09     0.0      0.0    10.4    -1.0    0.05
                97.64  101.35             65.3     12.3    17.0    30.2
LANDER RS
               102.66  105.98   102.94    -0.7      0.0    14.3     5.4    0.27
                98.65  102.75             70.6      8.0    16.6    25.6
2 HANFORD RS
               100.90  105.15   102.03     0.4      0.0     6.0     1.8    1.04
                98.73  102.75             34.0      5.1    15.0    21.1
1 HANFORD RS
               105.17  108.05                       0.0
               102.14                     -0.1
BRANDON RS
               103.55  105.91   102.10     0.3      0.2     3.3     0.5    0.01
                99.04  100.40             54.3      2.6    10.0    12.7
MICHIGAN RS
               102.17  105.93   102.05    -0.4      0.0     4.0     0.7    0.23
               100.36  101.65             47.0      3.3    10.7    14.0
NORFOLK RS
               106.37  110.50   103.58     0.1      0.0
               106.26  106.97            100.0      1.6     1.2     2.9
CHELAN RS
               101.55  108.01   102.41     0.6      0.0
               101.22  103.21             50.6      5.2             8.4
HARBOR RS
               108.51           105.96     0.1      0.1
               108.26  109.13             50.3      2.1             2.1
W MICH RS
               116.41
               107.40  108.37              0.0      0.0
                                          99.0      0.4     3.3     3.8
8TH SOUTH RS
               100.47           102.41     0.4      0.0     2.5     0.0    0.16
                98.26   99.58             34.0      2.5             2.0
```

FIGURE 46

HOURLY LOG

A feature of the logs is that if a particular item does not apply to a station, the space for that item is left blank so that only meaningful data items appear on the log. The log is constructed to allow a great deal of flexibility in the log format and to simplify changes.

LOGRHADL - Hourly Storm Log -- After data from each station is logged by the hourly log program, a request is made for the storm log program. A sample hourly storm log is shown in Figure 47. The storm log is only printed when there is significant information to be recorded.

LOGRDMND - Demand Log -- This program prints a log of data at a station or in a system at the request of the console operator. To initiate a request for a demand log, the operator pushes the desired station or system push button, the demand log push button, and the enter push button in sequence which initiates the demand log program to print the data for all requested stations.

The log and printing format is identical to the hourly log.

LOGRDADL - Demand Storm Log -- For each station printed on the demand log, a request is made for that station's storm log. If there has been any activity and there is significant data at any of the requested stations, that data will be printed after the demand log.

LOGRALRV - Alarm Review -- The alarm review program prints a summary of all alarm conditions present at a station or system as requested by the console operator. The operator presses the desired station or system push button, the alarm review push button, and the enter push button in sequence which initiates a request for the alarm review program.

The alarm review program first sends out a heading including date and time and then it searches for requests for an alarm review at a station. When a request is found, the data for that station are brought in. The station name is printed, and if no alarms are present, a "NO ALARMS" message is printed. For each alarm present, the alarm message is printed.

After completing the alarm review for a station, the program requests its own execution, and repeats the procedure searching for other requests for alarm review. If other requests are present, they are processed; otherwise, the program terminates.

```
06/25/73  0400  STORM LOG
        [illegible]  RAINFL  MAXRAT  OVRMAX  OVRVOL  OVRTOT
DEXTER RS
                                      0.0     0.00     0.76
[illegible] RS
                      0.01    0.06
[illegible] DENNY RS
                      0.00    0.00     5.4     0.06     1.24
LOC DENNY RS
                                       3.0     0.00     0.03
KING RS
                                       0.0     0.00     0.34
CONN RS
                                       0.0     0.00     0.23
LANDER RS
                                       0.0     0.00     0.05
2 HANFORD RS
                                      22.7     0.55     0.01
1 HANFORD RS
                                       0.0     0.00     1.29
BRANDON RS
                                       5.7     0.04     0.14
[illegible] RS
                      0.01    0.06
CHELAN RS
                                       0.0     0.00     0.02
HARBOR RS
                                       0.0     0.00     0.46
[illegible] RS
                      0.04    0.06
```

FIGURE 47

HOURLY STORM LOG

LOGRWQAL - Water Quality Hourly Log -- This program prints an hourly log of the data received by the Water Quality Monitor System which automatically scans five remote water quality stations (Renton Junction, East Marginal, 16th Avenue South, Spokane Street and Kent) each hour. This interval may be reduced or demand scans may be initiated which require that the first scan for a station during the hour be determined.

At fifteen minutes past the hour, the executive clock program requests the Water Quality Log. The program causes the console data logger to skip to a new page and print the titles including date and time and the column headings (see Figure 29). The water quality data file is then searched, starting from the back and working forward, for the first record for the current hour. Each record is accessed in sequence from that point for each successive station. The record is checked for proper format, and the characters are converted to ASCII text. If there are any errors in the format or if any characters are unrecognizable, the station name, the message "BAD DATA," and the converted record are printed with no reformatting. Otherwise, the characters are moved into the output buffer in a format that will line up with the printed headings and the station name and reformatted data are printed. If no data are available for a station, the station name and the message "NO DATA" are printed. This program is repeated for each successive station until data for each station have been printed.

Hydraulic Calculations

One of the major functions of the CATAD system is to convert analog data from the remote stations into trunk flows, interceptor flows and pump station discharges so that the flows can be used in storage calculations and for automatic control. Since these calculations are comparatively lengthy, they run at a low priority level to avoid delaying other more time dependent tasks.

Most of the analog data from remote stations is used for flow calculation. At regulator stations, analog data are received on gate positions and water levels; at pump stations, data are received for setpoint, wet well level, pump speeds and force main pressure. These data are sufficient for the calculation of flows.

Flows are calculated at regular intervals defined by the scan interval currently in effect at the station; flows are calculated every fifth scan on the even five or ten minutes after each hour.

So that no two executive levels write on identical disk files, newly calculated flows are not displayed on the console until the next regular or command scan of the station.

Regulator Station Flows -- Trunk and interceptor flows, diverted flows and overflows are calculated at each regulator station. Trunk flows are determined indirectly by totaling computed amounts of diverted flows, overflows and stored flows. Interceptor flows are computed from measured interceptor levels based on steady, uniform flow in the interceptor using Manning's equation.

Since backwater in the interceptor may extend upstream of a regulator or pump station, interceptor flow is calculated for both uniform and non-uniform flow conditions. Non-uniform flow is calculated by the difference in level between two stations. The lesser of the uniform and non-uniform flow amounts is used as the interceptor flow.

Diverted flows and overflows are calculated from measured values of gate position and trunk, interceptor and tide levels. Four hydraulic conditions (shown in Figure 48) have been considered in computing gate flows:

1. Non-uniform, open-channel flow (regulator gate only) with the gate out-of-flow and diversions controlled by losses at the return line entrance and by steady uniform or non-uniform flow in the return line.

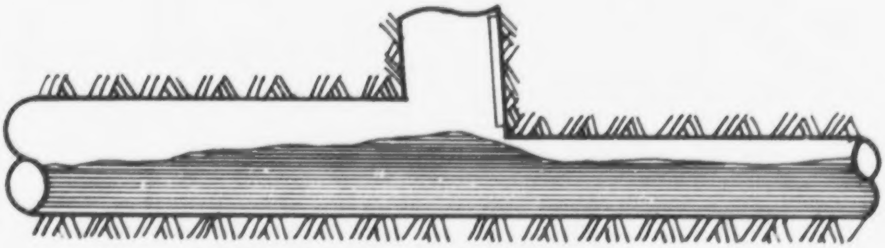
2. Non-uniform flow (regulator gate only) with the gate in the flow and the quantity of diverted flow controlled by losses at the gate and by steady uniform or non-uniform flow in the return line downstream.

3. Partially- or fully-submerged orifice or weir flow with flow controlled by the head difference at the ofifice.

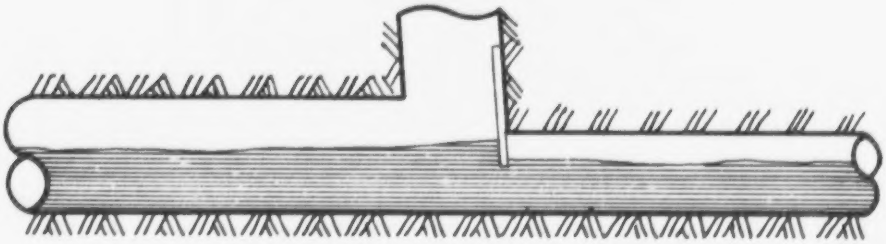
4. Free orifice or weir discharge.

The downstream head at regulator gates or weirs for conditions (2), (3) and (4) depend on the level of steady uniform or non-uniform sub-critical flow in the return line downstream and on mementum considerations.

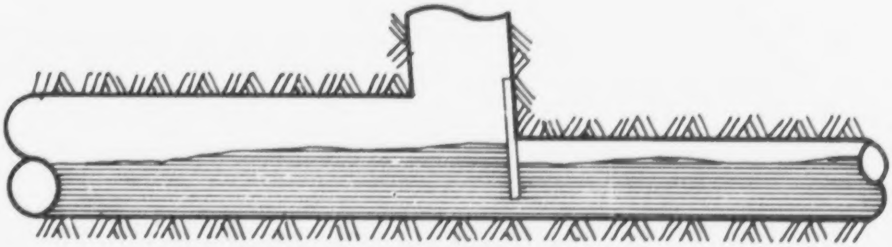
The level of steady uniform or non-uniform flow in the return line below the gate is determined by the level for steady uniform flow in the return line or a calculated backwater level from the interceptor. The level at the downstream side of the gate is computed from a relationship based on momentum of the gate efflux and of the steady flow below the gate. Depending on these conditions, the emerging jet may be partially or fully submerged or downstream flow may be swept by the efflux from the gate producing an hydraulic jump downstream.



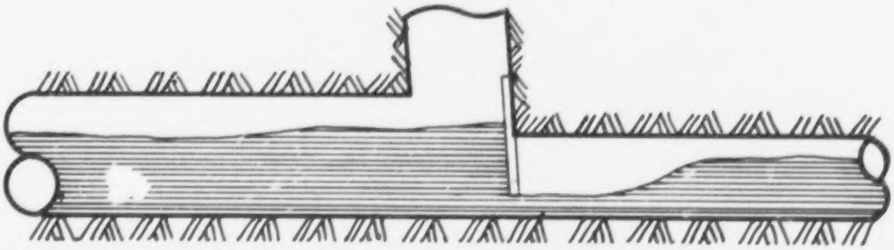
1. NORMAL DEPTH DOWNSTREAM



2. SLUICE GATE WITH DOWNSTREAM CONTROL



3. SUBMERGED SLUICE GATE



4. SLUICE GATE WITH FREE DISCHARGE

FIGURE 48

SLUICE GATE FLOW REGIMES

Since the quantity of diverted flow through the regulator gate depends on downstream conditions at the gate and these downstream conditions depend on the quantity of flow in the return line, the diverted flow is calculated by an iterative procedure. Only conditions (3) and (4) apply to the outfall gate, the downstream level being the measured tide level.

Pump Station Flows -- Pump station discharge is computed by three procedures:

1. From pump characteristic curves;
2. From differential pressures in force mains;
3. From flow meter measurements.

Pump flows may be computed on the basis of measured wet well levels and measured pump rotational speed from model or prototype characteristic curves. Since the pump discharges to a free water surface, the discharge head may be defined as the difference in elevation of the impellor center line and the free surface. The elevation of the free surface varies somewhat with flow but may be computed from the station geometry. The suction head may be determined directly and the discharge determined for the pump speed and head from pump characteristic curves.

At pump stations with long force mains, friction loss in the force main may be used to indicate flow quantity. Since the pump discharges to a free surface, a single pressure measurement at the lower end of the force main measures the head loss. At stations which have been calibrated as discussed elsewhere in this report, flow is calculated from the calibration curve which is a function of the single observed pressure value. This calculation is in addition to the calculation based on pump characteristic curves.

Flow meters in the West Point and Renton Sewage Treatment Plant effluent lines measure the discharge of the influent pumping stations. Since there is an appreciable time delay between the influent and effluent flows, the plant has a considerable levelizing effect on flows. Therefore, flow meter measurements are useful only for long-term comparisons of influent and effluent flow measurements.

Storage Calculations -- The volume of flow stored in the trunk during any time interval is computed by measuring level changes in the trunk at the regulator station. Since the regulator station is at the lower end of the storage reach, a level water surface is assumed for simplification.

Referring to Figure 49, the cross-sectional area at Section A between depths D_1 and D_2 at the beginning and end of the interval respectively may be computed from the trunk sewer geometry. The storage reach length L_1 at the beginning of the interval is the distance to Section B at the intersection of a level surface through D_1 with the surface of the flow at normal depth D_n on pipe bed slope S_b and is determined from the equation $L_1 = (D_1 - D_n)/S_b$. Similarly, the storage reach length L_2 at the end of the interval to Section C is $L_2 = (D_2 - D_n)/S_b$. The cross-sectional area of the pipe at Section B between depth D_n and $D_n + (D_2 - D_1)$ and at a section midway between Sections A and B may be determined from the pipe geometry. The storage volume between Sections A and B and between B and C may be determined by the prismoidal formula. The average storage rate during the interval may be determined from the storage volume and the length of the interval. In addition to computing storage volume during the interval, the remaining storage between the current and maximum trunk levels is also computed. This establishes the time remaining until all trunk storage has been filled at current storage rates.

The average inflow rate during the interval is the algebraic sum of the outflow rate through the regulator and outfall gates and the storage rate during the interval.

Since the actual change in depth during a ten-minute interval is usually less than 0.1 foot, the computed storage volume is sensitive to transient water surface disturbances. To eliminate the effect of such disturbances, observed surface level values are smoothed by regression techniques based on five or more preceding measured values.

During transient flow conditions immediately after opening or closing a gate or resulting from a rapid change in inflow, actual conditions may depart materially from the assumed level water surface in the storage reach. Although storage rate computations based on an assumed level water surface may result in substantial errors in calculated storage, such errors tend to average out as flow stabilizes. Calculated storage volumes are smoothed by regression techniques to damp out transient effects on calculated flows.

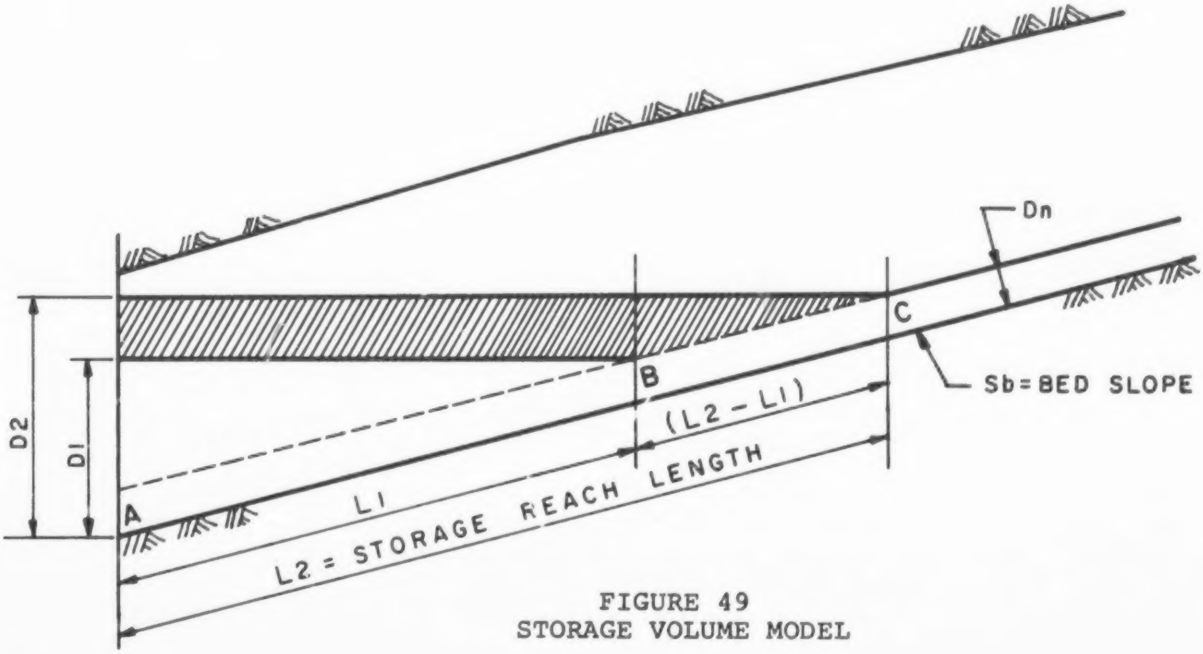


FIGURE 49
STORAGE VOLUME MODEL

Station Flow Control

Control of flow in the CATAD system is implemented by movement of regulator and outfall gates, trunk and pump station setpoints. Gate and setpoint movements described in Section V may be initiated by the console operator by direct position control or indirectly through use of flow control commands. To assure the safe operation of the system, numerous checks are made on console command requests to ensure that only valid commands are accepted and executed.

Direct Gate or Setpoint Control -- A request for a gate or setpoint movement initiates the command starter program. Any gate or setpoint position may be requested and a movement may be requested whether or not the gate or setpoint is presently in motion. The command starter accepts all requests, checks the validity of the request and decides when and whether to proceed with the command. When a command is already in progress, action on any new command is delayed until the first command is complete.

Requested Flow Control -- Routines are included for producing a desired rate of flow at a regulator or pumping station. One routine determines the regulator gate position required to divert the specified flow and a second routine determines the pump station setpoint required to discharge a specified flow at the station.

Every time station flows are calculated, stations with active requested flows are checked to see if sewage levels have changed enough to require a new gate/setpoint position.

Regulator Station Requested Flow -- A request for a specified flow at a regulator station is converted to a regulator gate position. The program calculates the maximum value of the diverted flow based on the current trunk level with the gate at the same level, or fully open if the trunk level is above the top of the gate opening. If the requested flow is greater than the computed maximum, the requested gate position is at the level of the trunk or fully open, whichever is lower. If the requested flow is less than the maximum, a gate position is assumed and the flow calculated. If the calculated flow is greater or less than the requested flow, a smaller or larger gate opening is assumed and the procedure repeated until the calculated flow is within prescribed limits of the requested flow. A requested flow of zero is interpreted as a request to close the gate completely if the regulator station is under supervisory control. The program will accept any positive value for the requested flow. A request for a negative flow is alarmed as an "invalid command." If the regulator station is in an automatic mode, the rate of opening a gate when releasing stored flow is limited; and if the interceptor is full, the regulator gate will be closed.

Pump Station Requested Flow -- A request for a specified flow at a pump station is converted to request for a specified setpoint. The pump station control equipment will increase or decrease the speed of a specific number of operating pumps (operating mode) in proportion to the wet well level within a specified band (see Figure 50). When the level rises above this band, an additional pump will be turned on. When the level falls below this band, a pump will be turned off. The pump speed may not be proportional to the wet well level throughout the band, but may maintain a full speed for a range of levels at the upper end of the band and minimum speed for a range of levels at the lower end of the band. The proportional controller for the new mode of operation then increases or decreases pump speeds as the level changes within a new proportional band. The number of modes is limited by the total number of pumps and the requirement that at least one pump be in operation at any time.

The pump station setpoint controlled by the computer is input to the pump controller in place of the wet well level permitting indirect control of station discharge via the pump controller. Pump controller operation is simulated by the program which computes the pump discharge at an assumed setpoint level based on the number of pumps on and the computed pump speed at this level. If the computed flow is greater or less than the requested flow, the assumed setpoint is lowered or raised accordingly until the computed flow is equal to the requested flow within prescribed limits.

The program can determine the maximum and minimum flows for the current operating mode, and if the requested flow is greater or less than these flows, a pump must be turned on or off as required.

If the pump station is in supervisory control, a flow requested by the operator is checked against the computed maximum and minimum flows for the current mode. If the requested flow is outside these limits, a message is printed on the console showing the maximum or minimum flow and the corresponding setpoint. If the operator wishes to change modes, and turn a pump on or off, he may enter a direct setpoint request which moves the setpoint above or below the mode change level of the pump station controller. He may then reenter the requested flow.

If the pump station is in automatic operation, the program automatically changes pump station operating modes without operator intervention.

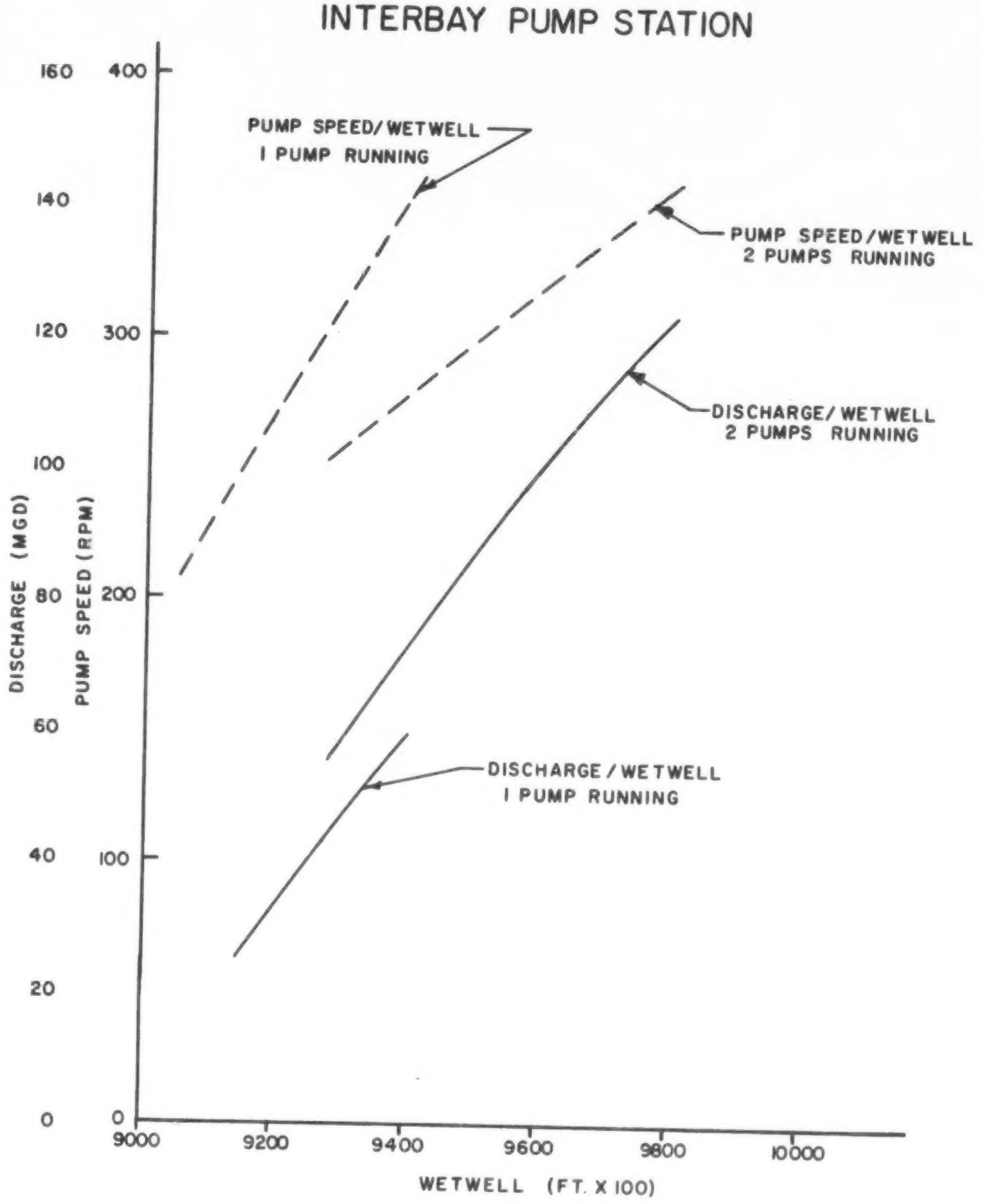


FIGURE 50

TYPICAL PUMP CONTROL PROGRAMS

AUTO CONTROL STRATEGY

Automatic control is a software control state which provides for unattended control of remote stations by the CATAD central computer. Whereas supervisory control permits requested flow, gate and setpoint commands to be entered by the console operator, only foreground programs may initiate commands under automatic control. Special control routines, running at executive level eight, determine appropriate requested flows and setpoints for each station in auto control. These flows and setpoints are affected by various conditions including interceptor flow, trunk level, trunk storage, tide level and conditions at downstream stations.

Objectives

The primary objectives of the automatic controls are:

1. To use the maximum storage in tributary trunk sewers to control flows in the interceptor sewers
2. To use the maximum capacity of the interceptor sewer to carry combined flows to the treatment plant
3. To limit flows into the treatment plant to the maximum plant capacity
4. To ensure safe and orderly system operation.

The procedure for regulating storage in trunk sewers is based on the use of desired storage versus time curves ("rule curves"). These curves establish the rate at which flow should be stored in each trunk sewer which, in effect, determines the rate of diversion into the interceptor.

Appropriate rule curves are calculated at regular intervals by the real-time model of the interceptor system. The curves are affected by the following parameters:

1. Direction of storm movement
2. Probable precipitation amounts
3. Probable duration of precipitation
4. Water quality criteria governing overflows.

The operating strategy used for automatic control is based on general hydraulic considerations and actual experience in manual operation of the system under supervisory control. Actual experience demonstrates that maximum use of available storage is achieved by maximizing the flow through the interceptors subject to the limitation that total flow into the treatment plant must not exceed the maximum plant capacity. It is only when allowable interceptor flow has been reached at one or more points in the interceptor that storing is commenced in the trunk sewers. Storage rates are controlled by storage rule curves determined by flow routing using the real-time model.

The automatic control procedure was conceived and implemented with system safety and integrity the paramount concerns. Automatic control will run, and run safely, without benefit of the hydraulic model, and can operate safely with arbitrary storage rule curves. The rule curves are considered tools for optimization, subject to the limitations imposed by physical and safety constraints.

Remote station control is achieved by using facilities available to the operator under supervisory control. They comprise:

1. Control of flow diversions into the interceptor sewer at regulator stations by direct control of regulator gates

2. Control of flow at pump stations indirectly through setpoint control (except at Kenmore P. S.)

3. Control of maximum storage in trunk sewers indirectly through control of high-level setpoints.

Functions 1 and 2 are controlled by the use of the "requested flow" function currently implemented for supervisory control. Function 3 uses the "setpoint" command implemented for supervisory control.

Software Control Modes

Three software modes have been set up to ensure orderly station control. They comprise:

INACTIVE - the normal dry weather condition
ACTIVE/STORING - during which the trunk is being stored in accordance with the station operating rule curve
ACTIVE/RELEASING - during which trunk storage is being released subject to limitations imposed by the permitted interceptor maximum flow and regulator gate opening rate limit.

Stations are transferred from mode to mode as conditions permit. To avoid unstable transfers between modes, transfers can only be from INACTIVE to ACTIVE/STORING to ACTIVE/RELEASING to INACTIVE and not in the reverse order.

Conditions for transfer from mode to mode are as follows:

INACTIVE to ACTIVE/STORING

either: Interceptor flow greater than 100 percent of maximum allowed interceptor flow.

or: Any station downstream is active/storing.

or: Trunk level is within one foot of local setpoint.

ACTIVE/STORING to ACTIVE/RELEASING

Interceptor flow less than 90 percent of maximum interceptor flow and no downstream station is active/storing.

ACTIVE/RELEASING to INACTIVE

Trunk level is two feet or more below local setpoint.

Description of Operation

Under dry weather conditions, all stations are in inactive mode: all flow at regulator stations is transmitted without any storage taking place, and all pump stations are operated to simulate local control operation. For wet weather operations, stations under CATAD control have been classified into four groups, as described below.

Regulator Stations -- Regulator stations fall into two categories:

1. Interceptor regulators, where sewage from a combined trunk sewer can be diverted into an interceptor or overflowed to salt water
2. Trunk regulators, where storage exits in a sewer but overflows either cannot occur or are restricted because discharges would be to fresh water.

See Table 15 for specific station classifications.

Interceptor Regulators -- When flow at an interceptor regulator station reaches 100 percent of maximum flow, it is placed in active/storing mode and the diverted flow into the interceptor is controlled to increase storage in the trunk as specified by a storage rule curve for the station. If flow in the interceptor exceeds the maximum flow, diverted flow will be reduced, thus violating the rule curve. Whenever a regulator station is placed

Table 15. CLASSIFICATION OF STATIONS FOR AUTOMATIC CONTROL

REGULATOR STATIONS

Interceptor	Trunk
Eighth Avenue South	Dexter
West Michigan Street	Lake City Tunnel
Harbor Avenue	University (Future)
Chelan Avenue	Montlake (Future)
Norfolk Street	3rd Avenue West (Future)
Michigan Street	Hanford Street #1 [a]
Brandon Street	
Hanford Street #2	
Lander Street	
Connecticut Street	
King Street	
Denny Way Local	
Denny Way Lake Union	

PUMP STATIONS

West Marginal Way
East Marginal Way
Duwamish [b]
Interbay
Henderson Street
Rainier Avenue
Belvoir Place
30th Avenue Northeast
Matthews Park
Kenmore

---

[a] This station is not a true regulator, and its only use is for emergency overflow.

[b] Provides data only; no command capability.

in active/storing mode, all stations upstream are also placed in active/storing mode and begin to store. The rule curves at the stations are set up, however, so that upstream stations tend to store slower than downstream stations. Once placed in storage mode, regulator stations will store up to 100 percent of allowed storage and then attempt to maintain that storage until conditions permit transfer to active/releasing mode. This can only be done when interceptor flow at the station is less than 90 percent of maximum allowed flow and no stations downstream are in active/storing mode. Once a station is placed in auto/release mode, it attempts to divert as much flow into the interceptor as allowed by the maximum interceptor flow for the station subject to a gate opening rate check until all storage is released. When most of the storage has been released, the station is placed in inactive mode and the regulator gate follows the trunk level.

Most regulator station trunk setpoints for local control are well below the level of the highest spring tides but are above mean high water (four feet above mean sea level). The setpoint provides storage in the trunk during the periods when tides above the setpoint would cause backflow of seawater if the outfall gate were open. Most regulator stations also have a maximum safe setpoint above which local backwater flooding might occur. This level is 12 to 18 inches above the local setpoint.

To ensure available storage in the trunks in the event that a spring high tide is predicted to exceed the maximum safe setpoint, the trunk setpoint is dropped to the local control position between the time that the tide level rises to within two feet of the local setpoint and the time that the tide begins to fall. When a station is in the inactive control mode, the setpoint is always maintained in the local position, regardless of tide.

Trunk Regulators -- These stations only begin to regulate flow when the pump or regulator interceptor station at the end of the trunk enters the active/storing mode. When the storage mode is entered, these stations store as specified by a storage rule curve. When the controlling interceptor station enters the active/releasing mode, these stations also begin gradually to release storage in a controlled manner to avoid sudden surges which might upset control stability in other parts of the system, and ultimately resume local control operation where the flow is not controlled at all.

Pump Station -- In interceptors carrying combined sewage flows, interceptor capacity is limited. However, some interceptors in the north end of the system, which carry only sanitary flows, have spare capacity, and therefore storage capacity. In addition, pump stations on combined trunk sewers have, under most conditions, spare storage capacity upstream. To provide best use of these varying types of pump stations under CATAD control, they have been divided into two groups for the purpose of automatic control:

1. Interceptor stations, where as much flow as possible is transmitted to the treatment plants to maximize interceptor flows

2. Trunk stations, which have available capacity, either by virtue of being on a combined sewer, or because only sanitary flows are handled. See Table 3 for classification of stations.

Interceptor Pump Stations -- As soon as wet weather is detected by significant increase in interceptor flow, these stations are controlled to run at the maximum station discharge, subject to limits imposed on pump speed to avoid cavitation damage to the pump impellers. Under this control philosophy, the level of sewage in the pump station wet well is drawn down as low as possible, making available as much interceptor capacity as possible. If the maximum allowed discharge at the station becomes lower than the actual station flow, the station setpoint (which controls the pump speed) is reduced to the wet well level so that the station no longer attempts to draw down the level of the wet well, and instead, only reacts to changes in flow after they occur.

Trunk Pump Stations -- These stations simulate local control operations until a designated controlling station downstream (pump or regulator) enters storage mode. When this occurs, the station begins to store on a rule curve until maximum allowed storage is reached at the station or the controlling downstream station enters active/releasing mode. When the downstream station enters releasing mode, it is a sign that spare capacity exists downstream and the trunk pump station also begins to release storage in an orderly fashion by gradually pumping down the wet well until normal local control simulation operation can resume.

Operator Controls

The console operator has three control functions available to him under auto control:

1. Automatic Control Function. The operator is free to enter stations into automatic control or remove them from auto control as he may desire. Commands in progress are halted when a station is put in auto control, and in most cases, may not be resumed until the fifth regular scan after the contact change occurred.

2. Rule Curve Duration. When a station is placed in active/storing mode, it begins to store along a rule curve. The time taken to store a trunk from 0 percent to 100 percent is the rule curve duration. A large rule curve duration produces a slow rate of storage; reducing the rule curve duration produces a faster rate of storage. This function only affects regulator operation when a station is in the active/storing mode.

3. Maximum Flow Function. This function provides the operator with a means of entering the maximum plant inflow permitted at the West Point Treatment Plant. Normally, this function reflects the maximum plant inflow as ascertained from the West Point plant operator. In special situations, however, reduction of the plant maximum flow can be used as a control tool to regulate flow to the plant.

REAL-TIME MODEL

Control Plan

The real-time model is at the top of the control hierarchy which comprises four principal levels of implementation as follows:

1. Local control (hardware)
2. Supervisory control
3. Automatic system control
4. Optimized automatic system control.

Each level is superimposed upon the next lower level and is implemented via hardware controllers or program routines at the next level. Control at each level may be exercised independent of controls at higher levels thereby permitting orderly program development.

The real-time model is the device for implementing optimized automatic system control. The model which is executed periodically under program control is used to develop an operating plan for effective utilization of available storage within Metro's combined sewers and separated sanitary sewers. Storage control is affected using a technique similar to that used for sewer basin flood management, in which available storage in the main and tributary system is utilized during the period of storm runoff based on an operating rule curve for each storage element, which defines planned amounts of stored runoff as a function of time. These operating rule curves are developed on the basis of computer studies in which historical floods are routed through a system model. Routing studies are generally made by batch processing on a general purpose computer. Similar techniques are used in the CATAD system except that an operating plan to regulate runoff by effectively using available storage in the storm water collection system is based on actual and projected rainfall patterns. The plan is implemented by adjusting the storage rule curves which determine rates at which the automatic control program will store runoff at various control structures.

Historical flows are used for setting up initial operating rule curves which are then adjusted dynamically by real-time analysis of observed rainfall and runoff data using a system model. The results of the real-time analysis are implemented by adjusting the rule curves in accordance with actual rainfall and runoff patterns.

The procedure for model analysis and rule curve adjustment is as follows:

1. Storm hyetographs are constructed by combining measured precipitation with an estimate of future precipitation based on various criteria including seasonal factors, the U. S. Weather Service forecast, the direction of storm movement, and the pattern of actual precipitation

2. The hyetographs are converted to inflow hydrographs entering the Metro sewer system by the unit hydrograph method

3. Combined sewage flows are routed through the trunk sewers down to the major storage control structures

4. Combined flows are routed through storage control structures and down to the treatment plant as specified by initial or improved storage rule curves and as limited by physical and safety constraints

5. A list of flow excesses (i.e., possible overflows) which were not absorbed by the interceptor system are used to adapt rule curves to reassign storage to:

    a. make the best use of available system storage, and

    b. assign overflows in accordance with water quality constraints.

For the purpose of converting rainfall to runoff, tributary areas have been divided into about 40 subareas. To facilitate flow routing, the sewer system has been subdivided into a network of about 70 pipes. Principal control features include: 12 regulator stations which actively control flow entering the interceptor sewer; and 10 pump stations, some of which have a potential for storage upstream.

Rainfall Prediction

The manufacture of hyetographs for use in developing runoff obviously can be profitably improved in the light of actual results. In the initial stage of model testing, therefore, only actual real-time rainfall data is used to construct runoff hydrographs using the unit hydrograph method. It is anticipated that provision will shortly be made to extrapolate actual rainfall data into an entire predicted precipitation event by using frequency, time-duration and intensity-duration analysis based upon seasonal factors and storm direction to predict future rainfall in a precipitation event.

There are presently six rainfall gages being monitored by the CATAD system. Of these, three are located in the tributary areas of combined sewers.

Runoff Model

Rainfall hyetographs are converted to inflow hydrographs entering the Metro trunk sewer system by the unit hydrograph method. The unit hydrographs were developed for each tributary subarea in the system using a method described in Eagleson (25) in which unit hydrographs are synthesized from various data including the shape and size of the tributary basin. The unit hydrographs have been simplified to a triangular shape for use in the runoff model, (see Table A-3, Appendix A).

Sanitary flow is represented by a small additional amount of equivalent rainfall applied to each subarea. A suitable sinusoidal pattern has been developed for the sanitary equivalent rainfall to represent daily peaks and troughs in the system's dry weather flow characteristics.

Routing Through Storage Reaches

The treatment of storage reaches in the model is related to the treatment of regulator stations, operating rule curves and interceptor capacity. The handling of storage by the Storm Water Management Model, which assumes that a storage length has finite volume but zero length, is insufficient for the CATAD model. This approach implies that there is no lag between the time a wave appears at the top end of a storage reach and the time that it arrives at the downstream end. Flow transmission times are significant for long reaches and a number of trunks in the Metro system with slopes shallower than 0.001 are several thousand feet in length.

The approach chosen for routing flows through storage reaches is intended to be compatible with the method used for storage computations in the CATAD system. The inflow hydrograph is routed through the storage reach on the basis of the continuity equation; i.e., the outflow from the reach during each interval will be equal to the inflow to the reach less the amount of flow stored during the interval. The change in storage during the interval is determined by the operating rule curve so that for a computed rate of inflow to the reach the outflow rate is determined by the rule curve. If the computed trunk outflow is within the regulator gate diversion capacity, and within the residual capacity of the interceptor, the trunk outflow hydrograph from the storage reach becomes the inflow hydrograph to the interceptor sewer. If, however, the computed trunk outflow exceeds the regulator gate diversion capacity or the residual capacity of the interceptor, the inflow hydrograph to the interceptor is limited to the gate capacity or the residual interceptor capacity. The remainder of the trunk outflow comprises a hydrograph of excess flow.

When storage in the reach is equal to the maximum storage in the trunk, all inflow must be directly transmitted through the reach with no net storage increase and outflow will equal inflow.

Control Elements

There are three types of control structures which have significant effect on the flows in the system:

1. Pump stations
2. Regulator/outfall stations
3. Inverted siphons.

Special routines have been written to describe the effect of these structures on routing of flow. Regulator stations, which are central to the utilization of trunk storage, have been simulated to closely approximate behavior of automatic control.

In real-time, the operation of a regulator station is affected by three constraints:

1. The storage rule curve
2. The maximum allowed flow in the interceptor
3. The maximum capacity of the regulator gate and the pipe connecting the gate with the interceptor.

Either the gate capacity or the maximum allowed interceptor flow will form an upper limit on diverted flow.

In simulation, the maximum interceptor flow is calculated for each station before the routing is performed. The maximum flows are calculated from the current capacity of the West Point Treatment Plant, and hydrographs of unregulated flows entering the system. In the event that physical limitations interfere with the ability of the station to follow the operating rule curve, the difference between the computed diverted flow and the maximum diverted flow is considered to be excess flow, or potential overflow.

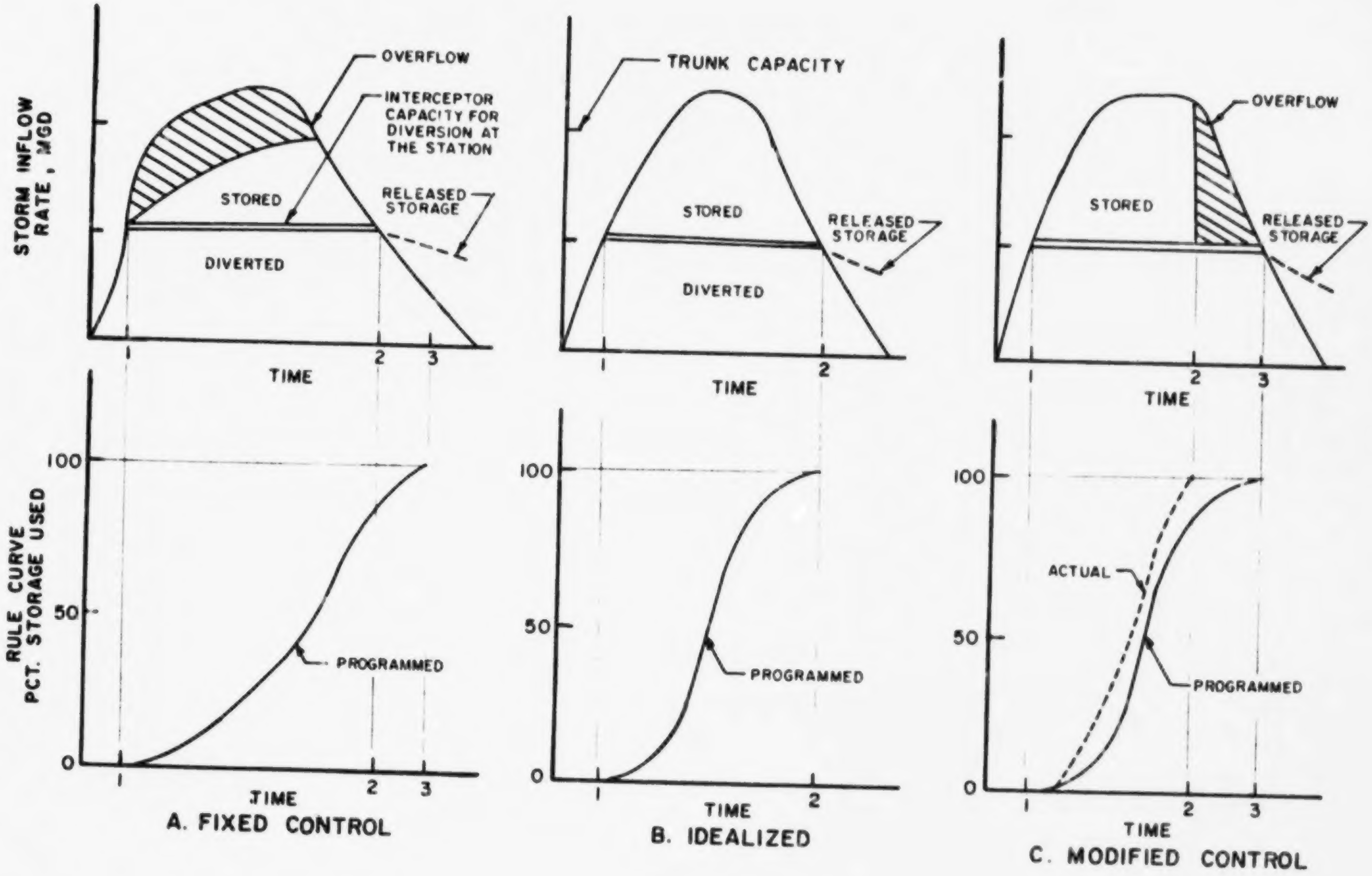
Rule Curves

The operating rule curve relates the rate of storage of sewage in a trunk sewer upstream from a regulator station as a function of the elapsed time from the beginning of the storm.

Basic operating rule curves have been developed from experience in operating the system under automatic control and from background studies. These curves are being expanded into a family of curves for various types of storms as a result of routing actual precipitation events. The primary difference in rule curves for various types of storms is the duration of time allowed for filling available storage. Since the number of potential storm patterns is essentially limitless, generalized rule curves for individual stations based on typical storms may not apply to a specific storm in which the geographical distribution of rainfall may differ considerably from the assumed storm. Nevertheless, the curves provide a point of departure from which to make more precise analysis using the hydraulic routing model.

Figure 51A shows that too strict an adherence to rule curves could cause some problems in the case of rapidly occurring storms. During the limited automatic control phase, programming has been developed which provides a modified rule curve control as shown by Figure 51C. This means the program will follow the rule curve until the rate of inflow greatly exceeds the storage rate of the control curve; then the computer will select the inflow rate itself and completely fill all storage in the trunk line before any overflow is permitted. (Note: The diversions and sewer configurations being discussed here refer to the diversion type regulator of Figure 5A).

Part B of Figure 51 shows the idealized control curve. The upper hydrograph shows that as inflow to the sewer increases, the programs will divert all this flow to the interceptor for treatment until the interceptor capacity at the point of diversion is met. At this point, commands will be issued to begin



A. FIXED CONTROL

B. IDEALIZED

C. MODIFIED CONTROL

FIGURE 51

STORM CONTROL WITH RULE CURVES

reducing diversion rates and storing excess inflow within the trunk sewer. The commands force the station to follow the idealized rule curve which, in the time period between time 1 and 2, makes use of 100 percent of the available trunk storage, holding the excess flow for later release to the interceptor.

Figure 51C shows what happens when inflow exceeds this idealized rule curve. The total hydrograph is larger than in the idealized case, and the design storage which can be managed by the programmed rule curve is insufficient to retain all the inflow from this larger storm without overflows. The control strategy is shown in the lower graph where the programmed rule curve is not followed, but the actual storage rate is determined by the rate of inflow in the top graph. Between time 1 and time 2, all storage in the trunk line is utilized. At time 3, after the overflow has taken place, the interceptor can accept additional flow and storage if released in controlled steps. This prevents excessive wave action within the interceptor from the rapid release of stored water from many stations.

Actually, the overflow shown in Figure 51C possibly would not take place because the limited automatic control program orders any upstream stations to begin active storing as soon as a station with heavy storm inflow exceeds its capacity to divert to the interceptor. Referring to the top hydrograph on Figure 51C, the program tries to increase the diversion capacity of the interceptor (raise the double horizontal line) by storing flows at upstream stations. Thus, the area above the double line would be reduced to an amount equivalent to the storage volume available in the trunk line. In this manner, the cross-hatched area, representing overflow volume, is reduced or eliminated.

Rule Curve Adjustment Using Optimizing Model

The result of routing flows through the interceptor system is a determination of stations with excess trunk flows and of stations with available storage. From these results, it may be determined whether there is net available storage or excess trunk flow in the system. In the first case, it may be possible to adjust station rule curves to eliminate overflow entirely. In the second case, station rule curves can be adjusted to reassign storage from trunks with potential overflow to trunks with available storage to reflect station overflow priorities, based on the relative impact on water quality of overflows into Puget Sound and overflows into enclosed waters such as the Duwamish River or the Lake Washington Ship Canal. This may be done by appropriately increasing or decreasing storage rates in the various trunk sewers. Experience has shown that overflows naturally occur first at stations that overflow into Puget Sound, and only rarely at stations that discharge into confined waters. The practical effect of the model analysis will, therefore, be to divert storage from stations at the downstream end of the interceptor system to stations having under-utilized storage capacity in the upstream reaches of the interceptor system. In instances where precipitation is local, model analysis will provide relief for portions of the system overburdened by runoff by storing dry weather trunk flows at the stations which handle separated sewage.

Related Background Programs

A collection of background programs has been developed to support implementation of the CATAD system. The program listing and documentation appears in Volume II of this report. Brief descriptions of some of the more useful routines are included here. Programs are used for data analysis and reduction or to diagnose features of the hardware and software.

Backwater -- Backwater consists of a group of FORTRAN routines designed to compute flow profiles in circular or horseshoe-shaped cross-sections under conditions of steady varied flow. The program contains specific subroutines to handle overflow weirs and other special structures in the North and Elliott Bay interceptors. There are routines to handle the Fremont inverted siphon, the Canal Street relief, emergency bypass structure in the North interceptor; and lowhead crossings at Lander and Hanford Streets in the Elliott Bay interceptor. Program use of special routines is controlled by parameters on input data cards describing the physical features of the sewer system.

Inflow from unregulated trunks and overflows from relief structures are calculated where appropriate. Inflow from unregulated trunks is computed as the sum of anticipated sanitary sewage flow and surface runoff calculated by the rational formula. Rational runoff coefficients for use in the rational formula (equation 1) were estimated by considering the nature of the areas in question, the existing tributary sewer system, and observed flow rates where available. Sanitary sewage flows were estimated from tributary population estimates.

$$Q = CiA$$

C = Rational runoff coefficient
i = Rainfall rate
A = Tributary area

Flow profile computations are carried out by the so-called standard step iterative method as described by Chow (27). Provision was made to add turbulence-induced head losses at channel expansions, contractions and changes in alignment.

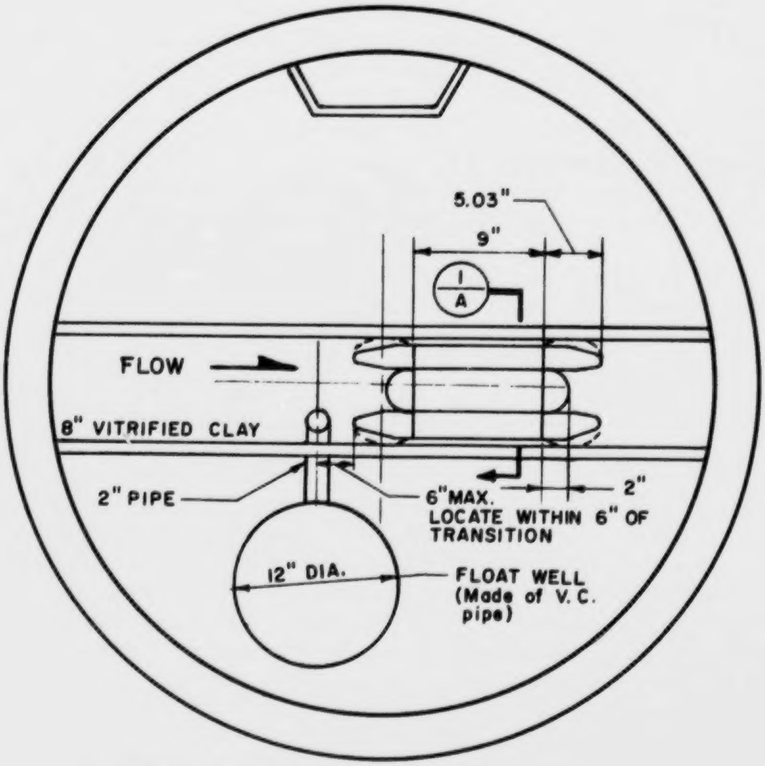
Flow profile computations are limited to subcritical flow (flow depth greater than critical depth) but can handle critical control sections that may occur. Each reach is tested for supercritical flow and its occurrence initiates a search upstream in the sewer for a control section from which profile computations may proceed.

Program input consists of data cards describing the sewer system physical features, and of operator input via teletype. The operator inputs external solution parameters including rainfall data, regulated trunk flows, and flow rate and water surface elevation at the downstream end of the system via teletype in response to program-generated messages. Upon completion of any set of computations, the operator can initiate a new run with new external parameters via the teletype.

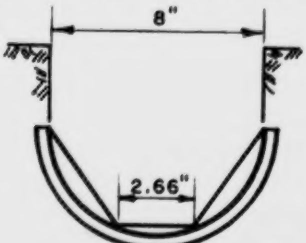
BACKWATER was designed to serve three functions. First it was designed to aid real-time inflow regulation to the North and Elliott Bay interceptors via the CATAD system in the supervisory mode. The operator can enter real-time rainfall data and proposed regulator inflows to get a prediction of interceptor response. The program can also be used with historical data to gain system behavior experience. The steady flow assumption limits this application. Second, the program may be used to simulate the behavior of proposed sewer designs under various flow conditions. Third, the program may be used to simulate the response of existing sewer systems to physical modifications. Effects on flow profile patterns can be examined prior to undertaking major modifications.

Palmer-Bowles Flume Rating Curves -- Metro has a large system flow measurement program to determine locations of excessive infiltration and to provide information useful in final development of mathematical models applicable to the CATAD system. Initial work in this study included programs required for rating the Palmer-Bowles flumes which perform this measurement in manhole locations around the Metro drainage area (see Figure 52). Manual flume flow calculations at various depths involved many hours of work with "Areddi" curves to establish a rating curve for the flume. Since this effort was required for more than 100 different measuring flumes in this study, a computer program was applied.

The program accepts basic physical data from the flume and upstream sewer line. The data includes sewer diameter, shelf height, flume side slopes, and elevation of vertical side slopes. The program produces a computer rating curve on the digital plotter (see Figure 53).


5.03"
9"
1/A
FLOW
8" VITRIFIED CLAY
2" PIPE
6" MAX.
LOCATE WITHIN 6" OF TRANSITION
2"
12" DIA.
FLOAT WELL (Made of V.C. pipe)

PLAN VIEW OF MANHOLE



SECTION 1/A

FIGURE 52

INSTALLATION OF PALMER-BOWLES FLUME

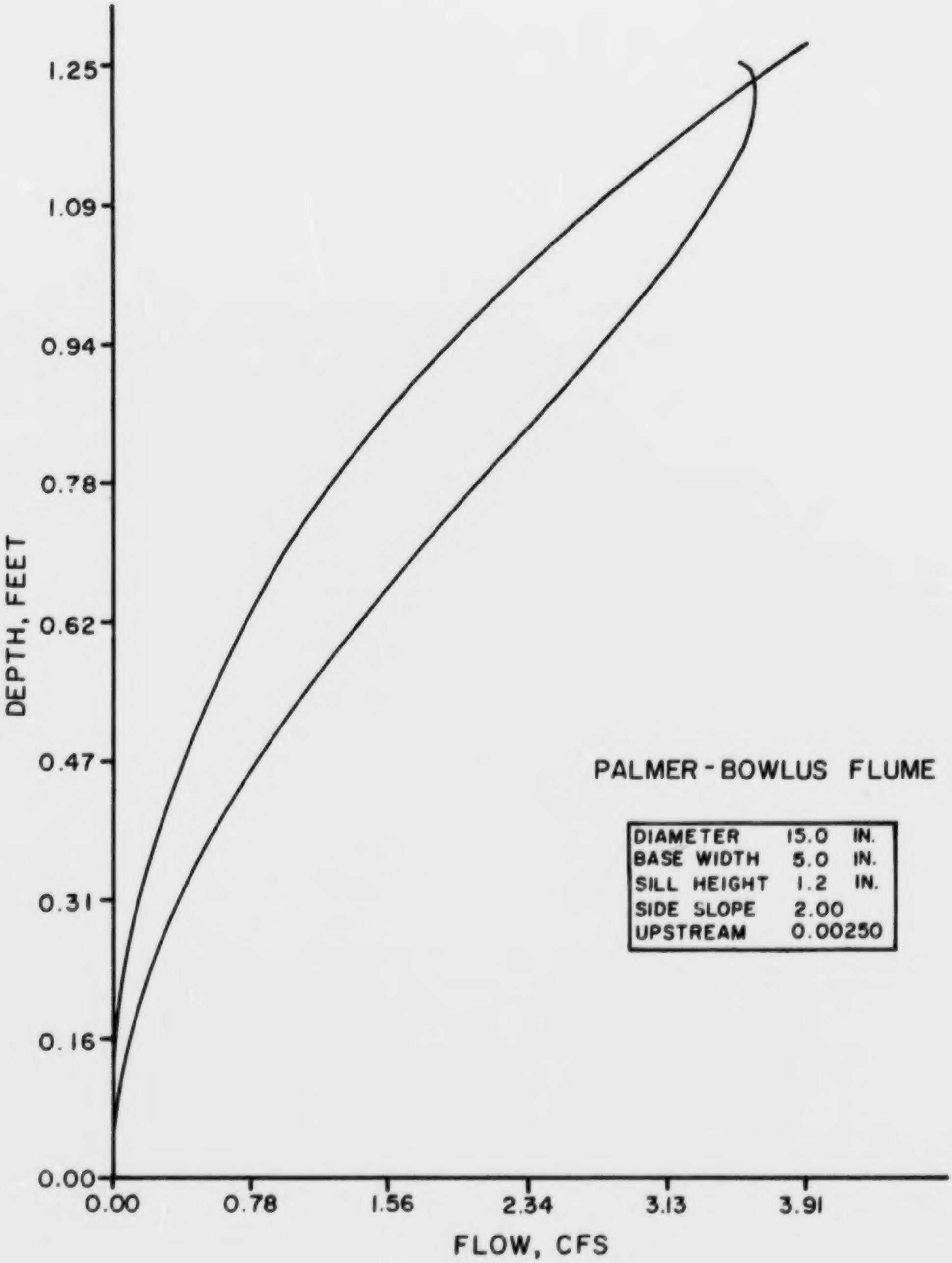


FIGURE 53

FLUME RATING CURVE

Monitor Data Retrieval -- Since 1966, Metro has continuously collected water quality data from remote sites on the Duwamish River. Before the Sigma II computer was available, data was transmitted via telephone lines to the central office, punched in paper tape and typed on a dedicated electric typewriter.

The paper tapes were collected and cards produced for data analysis.

The CATAD contract provided for the existing water quality monitor to interface with the computer and bypass the paper tape phase which would become a backup to computer collection. Data is now concurrently transmitted to the paper tape and the computer. Software writes the data on a large capacity random access disk (RAD) file. The file holds four days of data.

A data retrieval program takes the data from the RAD, formats it and punches cards for subsequent data analysis.

The RAD data is in a non-standard code which must be converted to EBCDIC prior to punching. Transmission is subject to failure and the data must be edited to assure that the punched cards accurately represent the measured parameters. The most frequent transmission problem is character duplication or character loss in transmission. Since a number of characters in the record are known (e.g., blanks, decimal point and end of record mark) these poorly transmitted records may be corrected or eliminated.

When the cards are punched, the file is cleared and the pointers are reset so the next data is properly located on the file.

Force Main Calibration -- A pressure transducer was installed in the force main at each pumping station to determine flow through the station. The salt velocity method was used to measure discharge; i.e., the pressure in the force main was stabilized at a measured level and then salt was introduced at the pump. A recording conductivity meter was installed at the end of the force main and synchronized with the time of salt injection. The resulting time vs. conductivity recording was digitized and a computer program determined the center of mass and, therefore, the transport time at that pressure. Force main pressure was then changed and the process repeated. Hydraulic aspects of this study are discussed in Section VIII. Here, program considerations are summarized.

Knowing the geometry of the force main and, therefore, its volume, it was possible to compute the flow at the measured pressure.

At the conclusion of a day's sampling, data was digitized and an attempt was made to fit the data with a curve of the form:

$$Q = Ap + Bp^2 + Cp^3$$

where A, B and C are constants determined by the method of least squares, and p is the dynamic head. Plots were generated to determine how well the generated curve fit the measured data and to determine where more data might be needed.

Computerizing the data analysis permitted investigators to decide whether more data was required at a particular station before calibration equipment was removed.

Examples of the Flow versus Dynamic Head curves are included in Appendix F.

Process Data Storage -- Hourly log data for each remote station in the system was judged too sparse to determine the station's reaction to changing physical parameters. The magnetic tape drive offered a means of obtaining great quantities of data, rapidly sorting out unwanted information and displaying the selected data for detailed analysis. During storms, a policy was established whereby the data collected from all regulator and pumping stations was saved after each scan on magnetic tape for a historical record and for data analysis. The program called PROCESS DATA STORAGE is stored in the disk library. To begin data storage, the tape is mounted, the drive readied and the operator types Q MAGBGN on the programmer's console. It replies by asking "what stations?" The operator types ALL or a unique code for a single station. By repeating the process, multiple stations can have their scan data stored on tape. A similar process is followed to terminate the data storage program.

Special control and/or hydraulic problems of a rapidly changing nature at any remote station can be singled out for a rapid scan rate as short as two seconds. Collected data is stored on the system magnetic tape for later analysis.

Data saved includes: the data displayed on the operator's console CRTs, analog inputs from each station, all contact status, the analog values converted to engineering units, and the contents of the rainfall pulse counters. This data is in addition to static data such as conversion factors, analog value ranges, maximum pulse counter rates, etc.

Process Data Retrieval -- The data on magnetic tape can be subsequently displayed in two forms: plots of data value vs. time, and tables of data values. Most often, the data is plotted using a program called PROCESS PLOT.

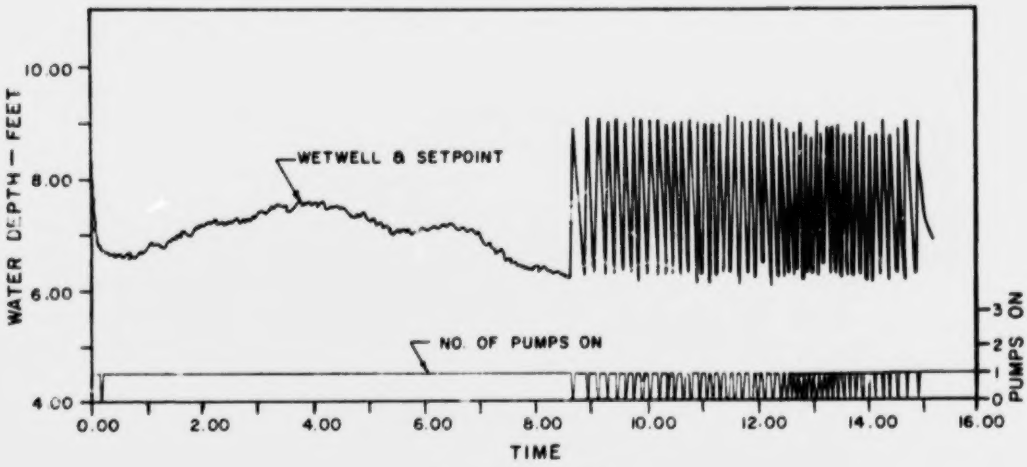
A card is read indicating which station is to be plotted. The required station is read from the magnetic tape and saved on the bulk memory unit (magnetic disk or RAD). A parameter card is then read indicating the date the tape was created, a code designating which variable is wanted and its factor, name and units. The specified variable is then read from the RAD and plotted. Another parameter card is read and the process repeated until all the required variables for the station are plotted. Examples of plots generated by this program are included in Appendix G.

Figure 54 shows how the data gathering and displaying programs in analyzing remote station control problems. In this case, pump mode controllers were functioning improperly and pumps were cycling on and off at a damaging rate. Faulty gate setpoint controllers, pump tachometers and other instrument malfunctions have also been investigated and corrected with CATAD acting as a centralized data gathering facility for the entire Metro system. There are obvious cost advantages for a centralized system compared to installing multi-pen recorders at each remote site or a "traveling" precision recorder set up at a station to analyze a specific problem.

Process Data Tables -- When exact process data values are needed rather than a graphical representation, the data from the magnetic tape is reported in tabular form. Data for more than one station may be listed. This program helps to assess the effects of station interaction.

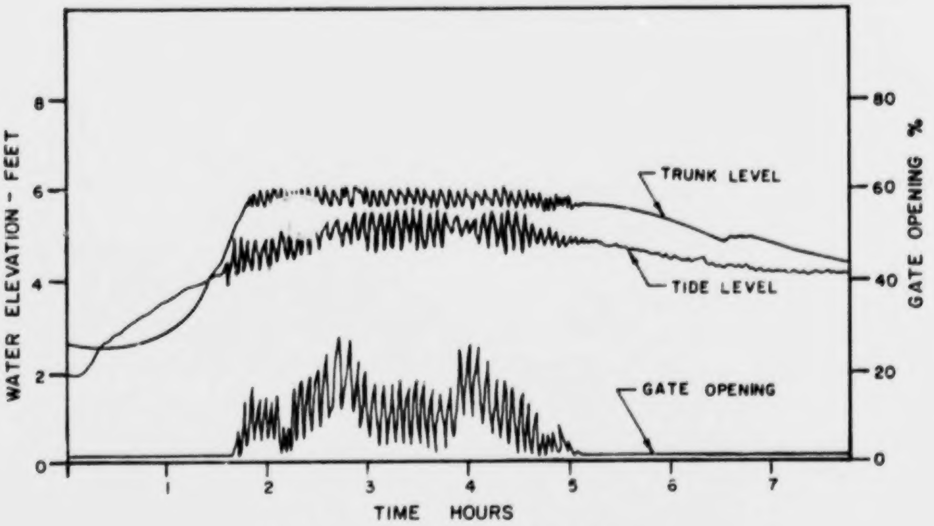
Program input includes: station number, number of scans to skip between reported record, variables and contact status to list. The option to skip records reduces the length of a table. If a station were on a one-minute scan for 24 hours, the table would have 1440 entries. With scans on a five-minute interval, the program could skip the intervening scans to give a 288 entry table.

Diagnostics -- To perform hardware maintenance while operating foreground control programs, a series of programs were written to diagnose hardware malfunctions. The computer manufacturer did not have on-line diagnostics for Sigma II peripherals. A special diagnostic program was written for each unit. Two of the more complex programs are discussed below.



A. CYCLING PUMP

EAST MARGINAL WAY PUMP STATION



B. EXCESSIVE GATE MODULATION

LANDER ST. REGULATOR

FIGURE 54

EQUIPMENT PROBLEMS

Magnetic Tape Diagnostic -- This diagnostic was written to detect three typical magnetic tape unit problems. The error conditions tested are:

1. Unsuccessful read operation
2. Unsuccessful write operation
3. Compare errors.

An unsuccessful operation is defined as M:READ or M:WRITE (XDS supplied monitor service routines) returning with the accumulator not equal to zero after an initiate and wait request for input or output (I/O). This may indicate an unrecoverable I/O error, incorrect record length or other error conditions documented in the RSU reference manual under I/O completion codes.

A compare error occurs when a buffer with known contents is written to the tape and subsequently read back and the read buffer is not identical to the written buffer.

The diagnostic writes 6000 records each 180 words long containing a known data pattern. The tape is then rewound and the 6000 records are read and compared with what was written. If the cycle was successful, it is begun again.

On the other hand, if a compare error is detected, the contents of the bad buffer are written on the operator's console with the data and time the error occurred. The tape is then rewound and read again to determine whether a read or write problem exists. The tape is then written again.

All three error types have been detected on both units. Compare errors are the most serious in that there is no way of detecting the error unless contents of the record are known. (If the contents are known, there is no reason to read it from the tape!) This could be especially serious if data that can't be regenerated is saved on tape.

Calcomp Plotter Diagnostic -- The plotter was bought directly from the manufacturer rather than supplied by Philco. A diagnostic to test the controller and the plotter drives the plotter to trace a circle and report transmission errors. Certain controller components were heat sensitive and caused plotter malfunctions; i.e., the plotter would lose its origin and draw eccentric circles. When the faulty component was replaced, the problem cleared up and the equipment provided a year of maintenance-free operation. However, it now appears that plotter operation is causing bad RAD transfers, thereby compromising the integrity of the real-time system.

Core Diagnostic -- As part of the field acceptance test, a diagnostic was developed to determine whether foreground programs were inadvertently writing in the background core area. The program fills the background with a known pattern and constantly checks the pattern for alteration. No problems have ever been detected by this diagnostic.

Fremont Inverted Siphon Hydraulics -- The Fremont inverted siphon shown in Figure 55 was originally constructed as a twin-barrelled structure with 60-inch and 48-inch conduits without provision for directing flow preferentially to either conduit. In 1972, the forebay and afterbay structures were modified to direct dry weather flows preferentially to the 60-inch conduit (see Figure 56). The modifications, undertaken to provide better cleansing conditions in the siphon and the upstream sewer, included construction of an ogee shaped outlet weir and an inlet weir for the 48-inch conduit.

The Fremont siphon modifications complicate hydraulic profile calculations. Four distinct flow regimes exist with corresponding control conditions. In three of these, the depth of flow upstream of the siphon depends on the energy and hydraulic grade line elevations downstream. Hydraulic profile calculations through the siphon also require distribution of the total flow rate between the two barrels to equalize head losses. Profile calculations involve a trial and error procedure requiring a knowledge of the hydraulic and energy grade line elevations downstream and the total flow rate through the siphon. A computer program was constructed to perform the trial and error solution for upstream depth given the above variables.

A water surface sensor was installed as part of the CATAD system in the Canel Street relief and emergency bypass structure approximately 180 feet upstream of the siphon forebay. This sensor controls upstream regulator stations to eliminate overflows of combined waste water at the relief structure. This sensor cannot determine flow rate in the interceptor or flow depth downstream of the siphon because of the complicated siphon hydraulics and backwater effects. A second water surface sensor was installed in the junction structure where the Central trunk joins the North interceptor. This structure, located near the intersection of Third Avenue W. and W. Ewing Street, is approximately 180 feet downstream of the siphon afterbay structure.

The water surface sensor in the Central trunk junction chamber will control the future Third Avenue W. regulator station which is part of the overall CATAD system. The sensor also serves two other purposes. First it provides a control point regulating inflow to the interceptor from the Interbay pumping station, which controls the hydraulic grade line elevation at the central

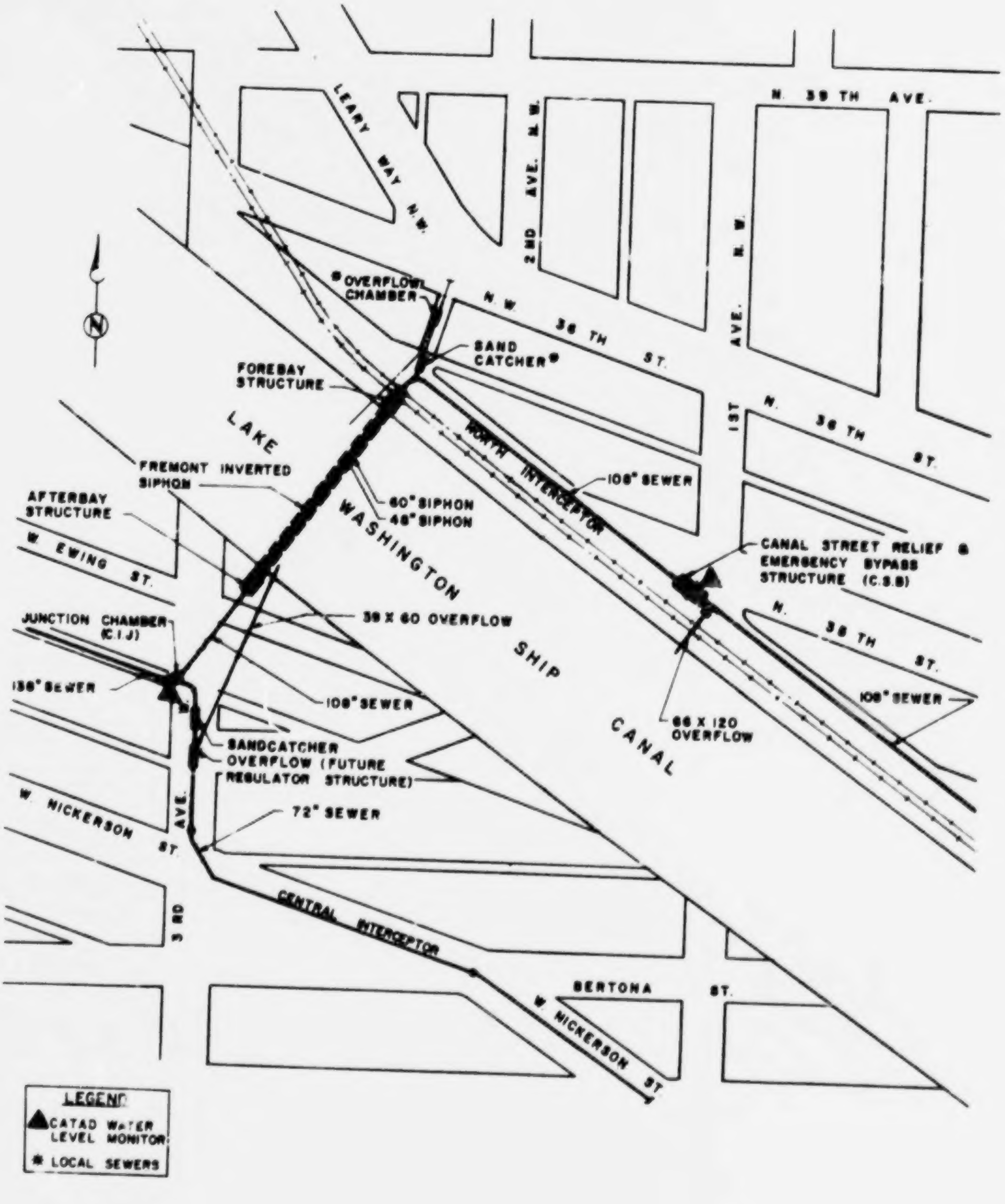

N. 39 TH AVE.
LEARY WAY N.W.
2ND AVE. N.W.
1ST AVE. N.W.
OVERFLOW CHAMBER
N.W. 36 TH ST.
SAND CATCHER
FOREBAY STRUCTURE
LAKE WASHINGTON SHIP CANAL
N. 36 TH ST.
NORTH INTERCEPTOR
108" SEWER
FREMONT INVERTED SIPHON
60" SIPHON
48" SIPHON
AFTERBAY STRUCTURE
W. EWING ST.
CANAL STREET RELIEF & EMERGENCY BYPASS STRUCTURE (C.S.B)
JUNCTION CHAMBER (C.I.J)
39 X 60 OVERFLOW
N. 38 TH ST.
138" SEWER
108" SEWER
108" SEWER
66 X 120 OVERFLOW
SANDCATCHER
OVERFLOW (FUTURE REGULATOR STRUCTURE)
W. NICKERSON ST.
3 RD AVE.
72" SEWER
CENTRAL INTERCEPTOR
BERTONA ST.
W. NICKERSON ST.
LEGEND
CATAD WATER LEVEL MONITOR
* LOCAL SEWERS
N

FIGURE 55

PLAN OF FREMONT INVERTED SIPHON & VICINITY

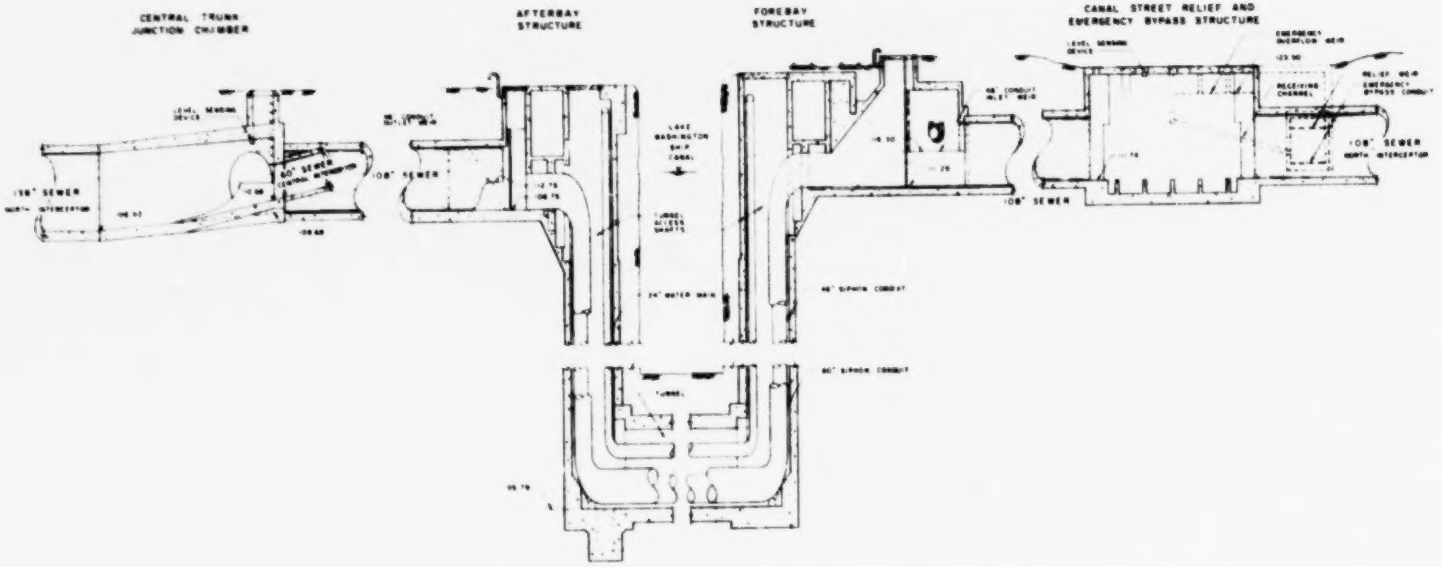

CENTRAL TRUNK
JUNCTION CHAMBER
LEVEL SENSING DEVICE
138" SEWER
NORTH INTERCEPTOR
60" SEWER
CENTRAL INTERCEPTOR
108" SEWER
AFTERBAY
STRUCTURE
LAKE WASHINGTON SHIP CANAL
TUNNEL ACCESS SHAFTS
24" WATER MAIN
TUNNEL
FOREBAY
STRUCTURE
48" CONDUIT INLET WEIR
48" SIPHON CONDUIT
60" SIPHON CONDUIT
108" SEWER
CANAL STREET RELIEF AND
EMERGENCY BYPASS STRUCTURE
LEVEL SENSING DEVICE
EMERGENCY OVERFLOW WEIR
RECEIVING CHANNEL
RELIEF WEIR
EMERGENCY BYPASS CONDUIT
108" SEWER
NORTH INTERCEPTOR

FIGURE 56

PROFILE OF MODIFIED FACILITIES, FREEMONT
INVERTED SIPHON AND VICINITY

trunk junction chamber. Second, it provides a means of computing flow rate through the Fremont inverted siphon. The water surface sensors at the Central trunk junction chamber and the Canal Street relief and emergency bypass structure indicate the change in water surface elevation through the siphon. This information may be used, via rule curves or other methods, to compute the total siphon flow without time-consuming trial and error flow balancing through the siphon conduits.

SECTION VIII

IMPLEMENTATION - OPERATION PROBLEMS

Considerable delay was experienced in implementing CATAD System Controls. Problems fall into the following major categories:

1. Programming Management
2. Problem Definition
3. Hardware Problems
4. Programming Problems

Electrical noise was an especially troublesome hardware problem and is covered in greatest detail.

PROGRAMMING MANAGEMENT

Specification Requirements

The CATAD System Control procurement specification required the system vendor to provide complete systems programs and some application functions. Metro retained responsibility of developing applications programs required for CATAD system automatic control.

Many major control systems suppliers provide standardized hardware using a specific computer; general purpose peripheral input and output devices; and various items of data acquisition, display, and control hardware. These suppliers also have standard system programs for these devices. From a cost standpoint, the user should utilize these standard programs as much as possible.

To use standard software, programming specifications must be predominantly functional. This procedure, unfortunately, gives a supplier who has not developed standardized hardware and software a great deal of latitude in developing specific system programs, and limits the owner's control of programming techniques used by the contractor.

CATAD specifications were functional for the most part, but defined some very specific program requirements:

1. A multiprogram priority executive system.
2. All input and output to computer peripheral equipment and to each specific item of special purpose hardware to be asynchronous and handled via a unique subroutine.
3. A system for debugging foreground programs on-line.

The requirement that input and output to each external device be under control of the executive system through a unique routine associated with that device is a practical necessity in a real-time system and serves the following objectives:

1. Permits queuing of multiple requests for use of a device.
2. Facilitates diagnosis and correction of hardware or program bugs.
3. Facilitates program changes to accommodate hardware changes.

Implementing Specification Requirements

Effective implementation of a computer directed real-time control system requires a systematic plan for program development. The plan should provide a logical development sequence from basic computer software to a comprehensive system.

The CATAD system contractor had not previously developed special software for the computer supplied for the CATAD system so he started with operating systems supplied by the computer manufacturer. The contractor prepared task-oriented programs, then attempted to integrate these individual tasks into a complete system. Each task comprised all input and output to the hardware device as well as the applications programs related to the device; all of which were attached to a hardware interrupt.

Applications programs were disk resident or used disk files requiring frequent transfers between the disk system and core memory. Hardware interrupt assignments were made without regard to time dependency of certain tasks. As a result tasks which might work satisfactorily when run independently, conflicted when run concurrently.

The contractor resolved many of these problems with considerble assistance from Metro's consulting engineer. Although resolution of these problems allowed the contractor to ship the system from the factory to Metro's site, it did not provide a truly usable system. The contractor's programs, while functionally acceptable, were cumbersome to use; imposed excessive overhead on the system; and were difficult to debug.

A logical development sequence that would prevent such conflicts was demonstrated in subsequent reprogramming, which was developed in the following sequence:

1. Preparation of overall system design
2. Preparation of system programs
3. Preparation of applications programs

The system programs described earlier in this report were not furnished by the contractor but were reprogrammed by Metro's consulting engineer to meet the original system specifications.

PROBLEM DEFINITION

A major problem encountered during CATAD system implementation was the contractor's inability to isolate problems to either the hardware or the program. Following the endemic industry pattern, hardware personnel pointed to programs and programmers pointed to the hardware. CATAD system development experience indicates that problems can generally be traced to four sources in roughly the sequence shown:

1. Program bugs
2. Inadequate hardware documentation
3. Hardware malfunctions
4. Hardware design deficiencies

A major program development problem was the apparent failure of contractor personnel to isolate problem sources by systematic plans of attack using the computer as a tool for problem diagnosis.

HARDWARE DIAGNOSTIC ROUTINES

Problems which require the greatest time to resolve often result from hardware malfunctions or documentation deficiencies. Such problems are difficult to isolate, and hardware personnel doubt their existence.

The most effective hardware problem isolation technique is a special hardware diagnostic routine which can provide either:

1. Raw values of computer input
2. Actual hardware response to computer output

This information can be compared with hardware documentation to ascertain whether the hardware is performing correctly.

HARDWARE PROBLEMS

A number of hardware problems were encountered during the contractor's original implementation as well as later. The principal equipment affected by hardware malfunctions were:

1. Disk Storage System
2. Interrupt System
3. Peripheral Equipment
4. Power Fail Detection
5. Remote Station Telemetry
6. West Point Satellite Terminal
7. Renton Satellite Terminal.

Many hardware problems encountered while the system was located at the contractor's facilities may be attributed to the environment, which exposed the system to contamination by dust through doorways open to the outside and to overheating in the absence of air conditioning. Many problems have abated significantly or disappeared since the equipment was moved to the central control facility in Seattle.

Other computer system hardware problems occurred at the contractor's facility during periods when preventive maintenance was postponed to avoid interference with programming. Regular maintenance was resumed when equipment failure delays began to cost more time than preventive maintenance.

Disk Hardware

Many problems were traced to the disk system initially furnished to the contractor. The disk has a substantial complement of spare tracks (about 20 percent). A number of bad tracks and other problems were encountered on the original disk, which was replaced. The newly designed replacement disk failed shortly after delivery. A second replacement was required.

The redesigned disk has subsequently proven highly reliable.

Computer Interrupt System

Problems have been encountered with random interrupts in the computer interrupt system. Although random interrupts are not difficult to correct, isolating resulting program execution problems may have been very time consuming.

Peripheral Equipment Failures

The most frequent hardware problems involved electro-mechanical peripheral devices, principally the card punch and card reader. Other problems were experienced with the graphic plotter and magnetic tape units which were interfaced to the computer buffered input/output channel by other than the computer manufacturer. This is a very complex interface with much critical timing. Problems have continued with these interfaces.

Card Reader -- Considerable problems were encountered with the card reader as originally furnished to the contractor. Replacing the read facilities with a fiber optic system effectively resolved the difficulty. This caused considerable delay during early programming.

Card Punch -- Card punches are notoriously troublesome and the punch supplied for the CATAD system was no exception. Heavy usage in the poor environment at the contractor's facility resulted in frequent malfunctions. Considerable skill is required to effect satisfactory repair. The entire punch mechanism has recently been replaced.

Keyboard Printer -- All the working parts of the keyboard printer, which is critical to programming, were replaced while at the contractor's facility.

Plotter -- The plotter interface initially presented major problems and interfered with disk transfer operations. The original problem was traced to an improper connection. However, periodic disk transfer problems appear to occur only during plotter operation. A mechanical plotter failure requiring return to the factory for parts replacement occurred within two years of the installation.

Magnetic Tape Unit -- The magnetic tape unit contained a number of design defects when installed. Although these defects were largely corrected, the units have not operated dependably and frequent tape transfer errors have been observed. Since the magnetic tape units are used for disk storage backup and for system generation, this problem has been a considerable annoyance.

Power Fail Detection Circuits -- Power fail detection circuitry is designed to interrupt the computer when voltage drops below a specified threshold. The computer then stores the contents of volatile hardware registers in non-volatile core memory available for restoration when the voltage rises above a specified threshold, higher than the power off threshold. The power fail detection threshold was initially set below the level at which the computer circuitry was reliable and the power fail routines operated improperly.

The problem was resolved by raising the power fail circuitry threshold as high as possible without causing the circuits to respond to normal transients.

West Point Satellite Terminal

Many hardware problems were encountered with the West Point Satellite Terminal at the contractor's facility. A persistent problem was associated with adjustment of delay line row write circuitry which was finally replaced by a solid state memory.

Other West Point Satellite Terminal design deficiencies were corrected by field wiring changes. Many of these problems were uncovered through the cooperative effort of hardware personnel and programming personnel of Metro's consulting engineer (see Program Problems).

Renton Satellite Terminal

The equipment for the Renton Satellite Terminal was procured subsequent to the equipment at the central station and under a separate contract. Numerous problems were encountered in implementing this terminal both in hardware and software.

The satellite terminal equipment comprised the computer, CRT terminal, keyboard printer and one end of the data link with the central terminal. Programming furnished by the supplier included only a real-time operating system and diagnostic routines to test the terminal hardware.

Field acceptance tests on a system of this nature are generally made so that, if possible, the testing includes only the hardware and software furnished by the supplier. The central processor, the CRT terminal and the keyboard printer were, therefore, tested using the supplier's standard diagnostic routines. The serial data link was tested using a local feedback loop in which a second communication adapter was installed and the output of the modem transmitter module was input directly to the modem receiver module. This arrangement is equivalent to a four-wire full duplex link and permitted testing of Renton terminal hardware independent of central station equipment and leased telephone circuits. From these tests, the equipment appeared to operate satisfactorily.

The hardware and software at the central station were designed to communicate with the West Point Satellite Terminal. Therefore, until the Renton Terminal software to emulate the West Point Terminal was available, the complete data link could not be tested and numerous hardware problems associated with the data link were discovered after applications programming was begun.

It is difficult to separate discussion of hardware problems from software and documentation problems since there is much overlapping. For this report the problems are separated on the basis of the source of the problem as finally uncovered.

The principal problems traced to hardware defects were as follows:

1. Defective core memory blocks (2,512 bytes)
2. Serial data link
    a. Adapter connections
    b. Modern connections
    c. Modern logic
    d. Modern relay noise interference with automatic I/O

For these hardware problems to fall under the normal warranty on the equipment, it is first necessary to demonstrate that, in fact, a hardware problem actually exists. Since the equipment had apparently performed properly during acceptance tests, the vendor will generally assume that subsequent problems are the result of program bugs or in the equipment of others.

Core Memory -- Two blocks of 512 bytes of core memory were discovered to have failed after the core memory had successfully passed core diagnostic tests after installation. The problems resulting from such a failure do not indicate their cause, and considerable effort is necessary to assign the cause to hardware or software.

Serial Data Link - The serial data link adapter provides the interface between the communications modem and the computer. Preliminary diagnostic testing of the data link adapter was done with the system in a "stand alone" mode; that is, input and output were done directly using hardware I/O instruction and bypassing the automatic input-output system. This mode is more suitable for checkout since it isolates the device from possible problems in the automatic input-output hardware or in operating system software. Problems were encountered in both receiving and transmitting via the serial data link adapter.

The normal sequence of operation is as follows:

1. The central station equipment in the "rest" state maintains the transmitted frequency in a logical "1" state.

2. The modem at the Renton Satellite Terminal translates the transmitted frequency as a logical "1" and presents it to the serial data link adapter which is in the "rest" state.

3. The central station equipment transmits a character which consists of a logical "0" (start bit), eight character bits and a logical "1" (stop bit) and returns to the "rest" state.

4. The appearance of the start bit at the satellite terminal receiver causes it to begin clocking on the new character.

It was discovered first that the modem was wired for a seven-bit character including parity rather than an eight-bit character including parity as specified. This was changeable through a strapping option.

After correction of the character format, the serial data link still could not transmit or receive. It was then found that the modem was inverting the transmission and translating a logical "0" as a logical "1" and vice versa. In the "rest mode" the SDL adapter at the satellite terminal was translating the "rest" signal as a continuous logical "0" which was interpreted as a start bit followed by eight "0" data bits, followed by another start bit, etc. The condition was corrected by interchanging two wires between the receiver and the control modules in the modem. Although the satellite terminal was then able to receive, it could not transmit. This problem was not resolved by a simple wiring change but required considerable testing using an oscilloscope and a detailed study of logic diagrams.

The modems can be operated in a two-frequency or three-frequency mode at the option of the user. In the two-frequency mode, the frequency is shifted between the mark or space conditions, i.e., "1" or "0" state, at the transmission frequency of the modem (base rate). In the three-frequency mode, the frequency is shifted up or down from the center frequency for the mark or space condition of each cycle of the transmitter and returns to the center frequency for one cycle. For the three-frequency option, a separate logic component controls the up or down shift. For the two-frequency mode, one of these components is removed. It was found that the wrong component had been removed. To correct the condition the other identical component, which is not required, was moved to the correct location.

After the data link had been modified to operate successfully in the "stand alone" mode, it then would not operate under the real-time operating system using the automatic input-output facility. After considerable hardware diagnosis using an oscilloscope and checking of software, the problem was traced to noise induced by contract bounce in a relay in the modem which caused an oscillation in the clear-to-send line from the modem to the data set adapter. This noise was causing a bit in the status register associated with the device to oscillate, which resulted in a series of erroneous interrupts to the computer. This modem relay is used to turn the transmitter on or off in a two-wire circuit. However, since a four-wire circuit is provided, the transmitter may be left in the "on" state at all times. The relay was, therefore, strapped in the "on" position and corresponding changes made to the software.

PROGRAM PROBLEMS

Detailed discussion of all programming problems encountered in implementing the CATAD system would be voluminous and contribute little to the state of the art. Some of the problems that were especially difficult to isolate, indicate some of the subtleties which may be encountered. Their resolution may be informative to others.

Principal programming problems related to the following areas:

1. Hardware documentation
2. Disk operating system
3. Power on/off
4. Executive and debug systems
5. West Point Satellite Terminal
6. Renton Satellite Terminal
7. Remote station telemetry

Hardware Documentation Problems

Experience shows that a major source of programming problems is inadequate definition of hardware operating characteristics by the designer. This particularly relates to actions required when an abnormal operating sequence is detected.

Operation must be defined for all possible combinations of external events and for all possible sequences of these events. These possible combinations and sequences of events must be defined for both normal and abnormal operation of the device hardware. Abnormal operation may include misoperation or malfunctioning of a device directly or indirectly controlled by the computer. For example, the computer may attempt to transmit a message to the West Point Satellite Terminal while the satellite operator is attempting to enter data. Often a system bug may surface as a result of an unforeseen combination or sequence of events (which the program cannot handle properly) months after the program has been thoroughly checked out. This can be diagnosed if a single routine controls the device.

Disk Operating System Problems

To build a real-time control system around a computer supplier's standard software, at least one member of the programming team must become intimately familiar with the software details. This is especially true in applications such as the CATAD system, where software features were tested to their limits.

A major problem was encountered in the disk operating system. Real-time data acquisition and control systems commonly acquire data via one program and perform appropriate control calculations via a second program. These tasks may be of different length, and are processed independently. The computer acquires data from one station and stores it on a data file while concurrently processing data from another station on the file. The disk operating system did not permit access to data from the same file by two programs running concurrently. A program attempt to transfer a file between core and disk storage after a lower level program had initiated a transfer of the same file caused a system hangup. (Note: This problem has been corrected in subsequent versions of the operating system.) The contractor did not analyze the problem systematically to determine the origin. The source of the problem was uncovered through detailed analysis of the operating system by Metro's consulting engineer who also proposed the solution. The solution consisted of a procedure for queuing all data transfers to or from the disk.

The newly designed computer operating system contained the usual complement of bugs which caused some delays.

Power On-Off Tasks

The power on and power off tasks in the operating system provided for a simple sequence of events; a power interruption followed by a restoration of power. However, actual power failure may comprise a sequence of events in which a circuit breaks open and automatic equipment at the switching station attempts to reclose the breaker. Thus the power on task may be interrupted while in progress by a second power failure. If the program is not prepared for this sequence of events, the system fails to operate.

The CATAD system power on task waits for about one minute before restarting the system after a failure to ensure that the restoration is permanent.

Executive System

The principal executive system program development problem was to incorporate the executive system with minimum modification to the computer operating system structure. This permits incorporating computer operating system improvements without major executive system changes. Thorough analysis of the operating system was necessary to achieve this objective.

An early executive system version developed by the contractor required a large number of transfers from the disk system to initiate a task, resulting in excessive system overhead. The present system minimizes disk transfers, significantly reducing overhead.

Remote Station Telemetry

Contact status input circuitry is installed for either 40 or 65 contact inputs. External devices may be connected to only a portion of these inputs. It was assumed that if no external device was connected, the input would appear to be in the open state. When this assumption was used in programming, spurious alarms occurred for non-existent devices because the hardware circuitry made a non-existent contact input appear to be closed. The data acquisition system program now masks out all non-existent contact inputs in status input data before checking for status changes.

West Point Satellite Terminal

West Point Satellite Terminal programming problems related to dual use of the terminal for two-way message communications with the central terminals initiated by the satellite terminal operator; and for transmission of random alarm messages initiated by the central computer to the satellite terminal. A series of central terminal alarms tied up the satellite terminal so that the operator could not enter emergency commands or request data displays. Under other conditions low priority data entry by the satellite terminal operator could preclude transmission of critical alarm messages from the central computer. If, in central computer polling or message transmission, the satellite terminal failed to receive the normal end of message code sequence, the satellite terminal would hang up. The terminal would accept neither messages from the central station nor any data entry at the satellite terminal. The condition could be cleared only by turning off the satellite station power supply and turning it back on again, reinitializing the logic. The logic could not be reinitialized from the central station. These problems were resolved by a combination of hardware and program changes.

The first problem was resolved by a program change giving the satellite terminal operator control of the data entry keyboard for a fixed time interval after he initiates a message transmission. The data entry procedure follows:

1. The operator depresses the "enter" button.

2. The central computer detects the request on its next poll and sends a message to the satellite terminal requesting the operator to enter his command or data request.

3. The operator has 30 seconds to enter a coded command or data request. During this time, no alarm messages will be transmitted and the operator is in control. If the operator does not transmit a message within the alloted time, any alarm messages waiting for transmission will be transmitted and the operator will have to reinitiate his entry procedure. To prevent the operator from interrupting an alarm message by depressing data entry keys at the

satellite terminal, a hardware logic change was made to the satellite station equipment. This change disables the entire keyboard when a beginning of message code is received from the central terminal and reactivates it when an end of message code is received.

The terminal hangup problem was corrected by a hardware logic change which enables the logic to be reinitialized by a start of message code. When the computer fails to receive a satellite terminal response indicating that the terminal has received a data message or a poll after three attempts, the computer transmits a start of message code to reinitialize the terminal logic and reinitiates the transmission.

Renton Satellite Terminal

The initial function of the Renton Satellite Terminal was to simulate the hard-wired West Point Satellite Terminal. It was not practical to require the supplier to furnish the system software since the operation of the satellite terminal involves interaction with hardware and software (which is non-standard) of the central station equipment. With divided responsibility for central station and satellite terminal hardware and software, the difficulty of determining problem sources would be extremely complex.

The programming of the satellite terminal was undertaken by Metro's consulting engineer, who was programming the central station. With correctly functioning hardware, a proven real-time operating system, and adequate hardware and software documentation, this should have been a relatively simple programming task. However, as a result of deficiencies in hardware, supplier furnished software, and documentation, the job became a nightmare. The interaction between hardware and software problems is discussed under the heading of hardware problems.

The software problems fall in two general categories as follows:

1. Operating system problems
2. Documentation problems

Operating System -- The real-time operating system was furnished as a binary paper tape. When the tape was loaded into the computer, the system failed to operate properly. It was found that the clock interval used for timing by the operating system was inconsistent with the basic hardware clock interval. The paper tapes furnished by the supplier were for a new model of the computer, which was not available at the time of the bidding. This new model is generally software compatible with the system furnished to Metro, but has a different clock cycle. The problem was temporarily corrected by a program patch until a correct tape was received.

The routine included in the system for operating the serial data link was not applicable to the CATAD system. The routines furnished were designed for communication over a two-wire half duplex data link, rather than the four-wire full duplex link which was furnished. Mode switching required for a two-wire link is inappropriate for a four-wire link. In a two-wire link the transmitter carrier must be turned on before transmission is begun by energizing a relay and turned off after transmission is complete by de-energizing the relay. A command to turn the transmitter on or off results in an interrupt when the transition is complete. The transmitter on-off relay had been strapped in the "on" state to eliminate contract bounce as discussed in connection with hardware problems. Therefore, no interrupt was received when the transmitter was commanded to turn on or off as expected by the routine. The routine was, therefore, revised for operation over the four-wire circuit which, in effect, simplifies the routine. At the same time the routine was modified substantially to revise the input sequence to facilitate use by applications programs.

Documentation -- The CRT display and the keyboard printer would not respond to commands under the real-time operating system although they would operate using the supplier furnished diagnostic errors in the documentation which gave incorrect addresses for both devices.

A major problem resulted from errors in the basic documentation of machine language codes for three logical operations and one input-output operation. The supplier's documentation was used to create a cross-assembler to enable the programmer to assemble programs for the Renton terminal minicomputer on the central station computer. This makes the more convenient and faster peripheral equipment at the central station available for assembly of programs for the minicomputer which has only paper tape for program input and output. By using the cross-assembler the programmer may prepare his programs on punched cards, which facilitates program editing, list his assembled programs on the high speed line printer and punch his object programs on paper tape for entry in the minicomputer. The errors in documentation resulted in the generation of incorrect program code by the cross-assembler. The documentation errors were discovered after much time and effort and the cross-assembler revised accordingly.

FLOW CALCULATIONS

CATAD system planning anticipated that flows calculated from manufacturers' pump unit performance curves might prove unreliable, since sewage pumps operate in a harsh environment, pumping abrasive solids and corrosive solutions. Abrasion of pump impellers, solids deposited in pump unit intake sections, and particularly recirculation due to abrasion of the impeller housing wear rings were expected to degrade pump unit efficiency relatively quickly. Actual operating experience indicates that this degradation takes a period of years and that pump efficiency is not likely to drop more than 20 percent before worn wear rings are replaced and other necessary maintenance is performed. Experience with calculated discharges for the pump stations in the system leads to similar conclusions. Manufacturers' pump unit performance curves may be used to calculate reliable flows provided that critical analog sensors, particularly pump speed sensors, are reliable.

Because flows calculated using performance curves were considered dubious, force main pressure sensors were installed at many pump stations to provide alternative means of calculating station discharge. An extensive program was undertaken to calibrate the pressure gages using the Allen Salt Velocity Method. Flows generated by these gages have not been entirely reliable because of rapid fluctuation of analog pressure values. Pressure variation of 2 percent of full gage span can alter the calculated flow by as much as 10 to 20 percent. Force main pressure values are filtered before being used to calculate flow.

Suction head at the pump stations is measured by a wet well level sensor. There is no provision for direct measurement of discharge head at any station, although discharge head is needed in flow calculation. Initially, the static discharge head was assumed constant, defined by the elevation of the pump invert or of the crest of a discharge weir at the downstream end of the force main. This assumption was inadequate, and an iterative procedure was used to calculate depth at the downstream end of the force main. A depth was assumed at the end of the force main and an assumed discharge head was obtained. The computed force main discharge was compared with the computed pump discharge and depth calculations were revised until the computed pump discharge and the force main discharge agreed.

Extensive testing of storage calculations revealed two deficiencies in the flow calculation procedures for regulator stations. No allowance has been made for the effect of interceptor backwater affecting the tailwater at a regulator gate and no transition had been provided between fully-submerged and free discharge conditions. A backwater allowance was added, and a method of calculating the degree of gate submergence was developed.

Trunk Inflow and Storage Calculations

Considerable effort has been expended to find a workable method of calculating storage in trunk sewers upstream from regulator stations and inflow to the storage reach. The problem results because upstream conditions (i.e., inflow into the storage reach) are computed from observed downstream conditions. Since inflow changes occur independent of downstream conditions, they appear downstream after a delay equal to the wave travel time. Unsteady flow equation solutions must, therefore, assume a fixed relationship between inflow and depth at the upper end of the storage reach since neither is measured directly. This assumption is satisfactory unless the inflow rate of change is altered, which may result in an unstable solution caused by the time lag between the inflow change and the corresponding downstream level change.

Three development methods were attempted to solve the calculation of storage:

1. A direct finite difference solution of the unsteady flow equations;

2. A modified finite difference solution of the unsteady flow equations, using simplified steep-fronted waves in an idealized storage reach to represent changes in flow;

3. A method based solely on a continuity relationship with a simplified water surface profile.

Method 1 was tested using various inflow predictions. Solutions were rather lengthy and showed instability when large flow changes were imposed at the upstream or downstream ends of the storage reach. Method 2, which relied on modeling surges in the storage reach, gave incorrect results when compared with actual test data. Method 3, a direct approach, requires little iteration and gives results acceptably close to test data. However, the computation exhibits a tendency to over-react to large flow changes as did Method 1, requiring heavy damping of results. Method 3, which is currently in use for real-time storage and inflow computations, only satisfies the equation of continuity (i.e., outflow = inflow + change in storage).

Pump Station Control

Pump station control experience indicates that special care must be taken with smaller pump stations in the system, where major wet well level changes can occur in five minutes or less. A station in automatic control is normally checked every five scans to determine if control action is needed. Under dry weather conditions, control action is normally initiated every ten minutes. It became apparent that this is too long for some smaller pump stations, which can pump their wet wells dry in ten to fifteen minutes. To ensure safe small station control, each station is assigned a maximum scan interval which cannot be exceeded when the station is in automatic control as well as a specific number of regular station scans between control checks. Each station is controlled on a schedule appropriate to its operating characteristics.

Flow Routing

The critical part of the system hydraulic model is routing flows through open channel sewers. This task requires a solution, or an approximate solution, of gradually varied unsteady flow equations. A number of investigators have applied themselves to solving unsteady flow equations and have attempted to alleviate the two major problems confronted; ensuring a stable solution, and avoiding lengthy solution time. Routing model development also faced the difficulties of assuring a stable unsteady flow analysis under conditions of gradually varied open channel flow and of selecting a solution which can route 30-40 point hydrographs through a 70-element pipe system within the constraints of real-time control.

Three approaches to solution of the unsteady flow equations have been tried:

1. Direct finite difference solution
2. Method of characteristics solution
3. Modified finite difference solution

Initially, a direct finite difference solution was attempted. It proved to be unusable. A solution using the method of characteristics was developed successfully and provided acceptable results in test cases. It was extremely time-consuming, however, requiring subdivision of pipe reaches and exact definition of boundary conditions at numerous intermediate points in the sewer transport system. A modified finite difference solution developed for the Storm Water Management Model was tried and found acceptable. This is not a true solution of the unsteady flow equations, as it does not reconcile depths between pipe reaches. It has the advantage of swift solution and the ability to handle long reaches. It cannot be used for storage reaches where backwater exists because flow/depth relationships are defined by a modified Mannings equation where depth is a direct function of flow. In such cases, a normal routing is made to the end of the storage reach including travel time through the reach. Actual travel time is less through the deeper storage reach than for the assumed normal flow. The inflow to the storage reach is then routed through the reach based on continuity alone, the amount stored being assumed to conform to the storage rule curve. The amount stored is limited by a family of curves relating inflow to available storage.

ELECTRICAL NOISE EFFECT ON SOLID-STATE SYSTEMS

Although solid-state digital equipment susceptability to electrical noise -- that is, random or spurious signals -- has long been evident, preventive measures are difficult to apply in an industrial environment. Regulator stations are small and scattered through an industrial area where electrical interference is severe. The original design isolated the digital equipment in its own separate metal enclosure to provide some shielding. All incoming cables were shielded and analog cables had additional shielding on each pair. In addition, status wiring was run only a few feet in these cables. All status points were fed from nearby interposing relays.

Random station noise problems were noted from the time of the first installations. However, computer system operational problems prevented orderly assessment of noise effects. Even normal electronic instrumentation equipment installation for CATAD interface at Harbor Avenue regulator station presented extreme and unusual instability problems. Since the station is located in the area occupied by a moderately large steel mill, the mill's activities were immediately suspected. Measurements made with the engineer's oscilloscope showed a familiar voice-modulated envelope on every terminal and conductor in the station. The source was an A-M broadcast station whose transmitter was located nearby. The problem cleared up a few days later when a bulldozer accidently knocked over the transmitter tower.

After the CATAD system began regular reporting, it became apparent that much noise was generated by relays and contractors within each remote station. Relays operating frequently, such as those associated with the pulse generators, and the pulse generators themselves, were thought to cause many communication failures.

A task group was set up in February, 1973, to evaluate this problem and recommend solutions. Preliminary checks of several stations showed that some telemetry circuits presented more communication problems than others. Oscilloscope techniques showed that many problems -- false alarms and lack of accurate command capabilities-- were caused by adjustment of the modem receiver bias at both the central station and the remote stations. The adjustment was extremely critical and slight maladjustment caused erratic loss of transmitted data. After these adjustments were made, the stations performed acceptably, but not ideally. The task group obtained authorization to use outside consultants with suitable test equipment to evaluate the noise problems and recommend steps to alleviate false triggering of the TCU's input circuits. The consultant chosen was the Electromagnetic Interference Group of The Boeing Company in Seattle. They made measurements over a two-week period and submitted a detailed report with recommendations for limiting the effects of external noise on the TCU and for improvements within the TCU. (28) Their report was favorably reviewed and the task group's final report was submitted to Metro. The task group had already recommended TCU modifications; shielding modem input leads within the TCU and frequent bias adjustment checks by the maintenance contractor. Additional Boeing Company recommendations are presented in steps. First, they suggest addition of a power line filter; second, addition of ceramic capacitors to several sections of the logic busses within the TCU; and third, the correction of timer induced transients (pulse generators) by modifying or replacing the existing pulse generators and associated relays. They suggest that these steps be taken prior to considering more complex and costly measures.

The task group feels that digital equipment susceptability to random noise -- even that generated by a miniature relay -- is the major weakness of such systems. Present day state-of-the-art permits digital equipment in almost any location. Metro's noise problem is not unusual, but quite common. Much of the research in this area has been directed to designing solid-state input and output components and high noise immunity logic systems that are less susceptible to random voltage spikes. (29, 30).

The availability of input/output isolation systems incorporated in basic equipment led the task group to recommend that future TCU's be specified with new designs using the latest isolation techniques.

LAKE CITY TUNNEL SURGE

The Lake City tunnel facilities were first utilized for storage in 1971 after completion of a tunnel regulator gate station. These facilities are shown in schematic form in Figure 5. In 1972, system modifications provided a diversion from the Green Lake trunk sewer into the Lake City tunnel so the Municipality could repair a section of 138-inch trunk sewer lying downstream of the diversion. While the diversion was in effect, hydraulic transients in the Lake City tunnel system were so great that, on at least two occasions, sewage overflow occurred at the north portal of the Lake City tunnel. These hydraulic transients took place during extremely high flows in the entire sewerage system.

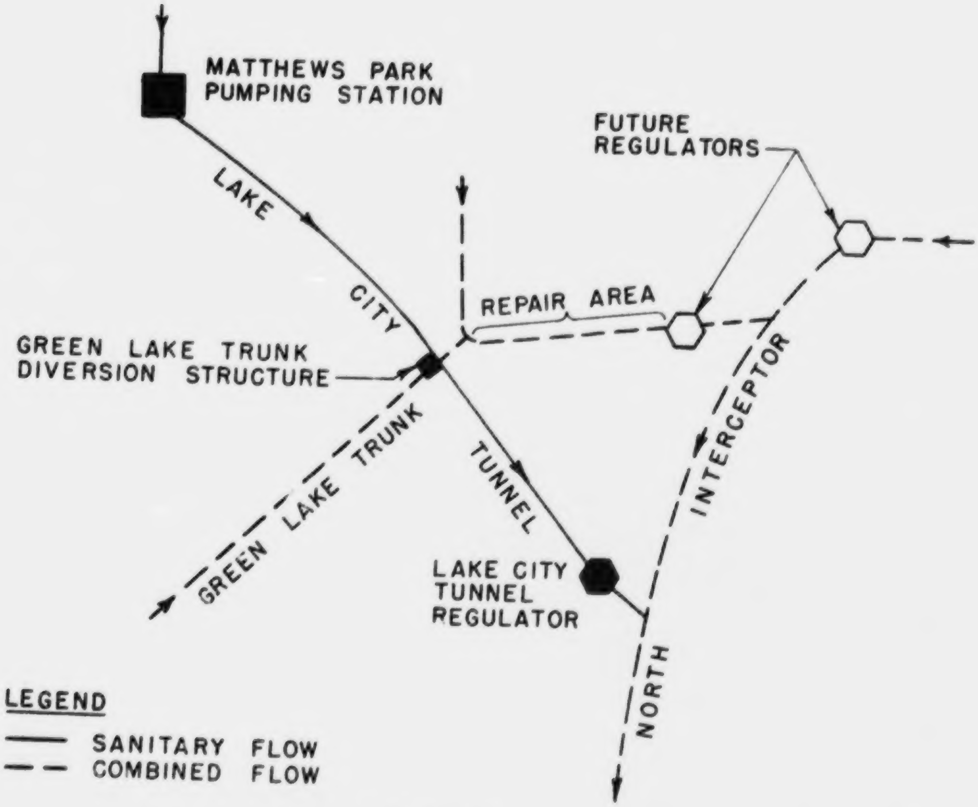

MATTHEWS PARK
PUMPING STATION
FUTURE
REGULATORS
LAKE
CITY
REPAIR AREA
GREEN LAKE TRUNK
DIVERSION STRUCTURE
TUNNEL
INTERCEPTOR
GREEN LAKE TRUNK
LAKE CITY
TUNNEL
REGULATOR
NORTH
LEGEND
SANITARY FLOW
COMBINED FLOW

FIGURE 57

LAKE CITY TUNNEL SYSTEM SCHEMATIC

Facility Description

The Green Lake diversion structure consists of a modified existing caisson structure on the Green Lake trunk sewer and a 48-inch diameter conduit connecting to an existing access structure on the Lake City tunnel (see Figure 58). The existing Green Lake trunk sewer caisson was divided with a wall containing a 36-inch x 36-inch sluice gate installed in the flow line of the trunk sewer. The caisson wall was extended vertically with the top forming a weir crest over which trunk sewer discharge in excess of the capacity of the 48-inch interconnecting conduit could return to the downstream 138-inch conduit.

This bypass or diversion structure was constructed to facilitate repair of 6900 feet of 138-inch existing trunk sewers. All reclamation work on the downstream facility was done from inside the 138-inch conduit. A continuous water stage recorder installed in the Green Lake trunk sewer caisson monitored water surface elevation and provided an indication of flow diverted to the Lake City tunnel. Green Lake trunk diversion to the tunnel commenced November 1, 1972, and remained in continuous operation until March 2, 1973, when the discharge was returned to 138-inch conduit. Diverted flow averaged approximately 18 cfs and varied from 7 to 41 cfs during dry weather. With the onset of storms, the diverted flow increased markedly with peak rates sometimes exceeding 180 cfs diverted to the Lake City tunnel.

The Lake City tunnel system under the operating conditions during late 1972 and early 1973 consisted of five primary elements (see Figure 59). These elements are:

1. A drop structure just downstream of the Lake City tunnel regulator providing a means for lowering the flow in the Lake City tunnel to the North interceptor system.

2. The Lake City tunnel regulator.

3. The Lake City tunnel consisting of approximately 17,400 feet of 96-inch conduit transporting sewage between the Lake City tunnel regulator and the Matthews Park pumping station.

4. The Green Lake diversion structure approximately 6000 feet upstream of the regulator.

5. The Matthews Park pumping station and its force main.

Three of these elements have static operating characteristics, while (1), the regulator and (5), pumping station, operational characteristics are controlled by the CATAD system.

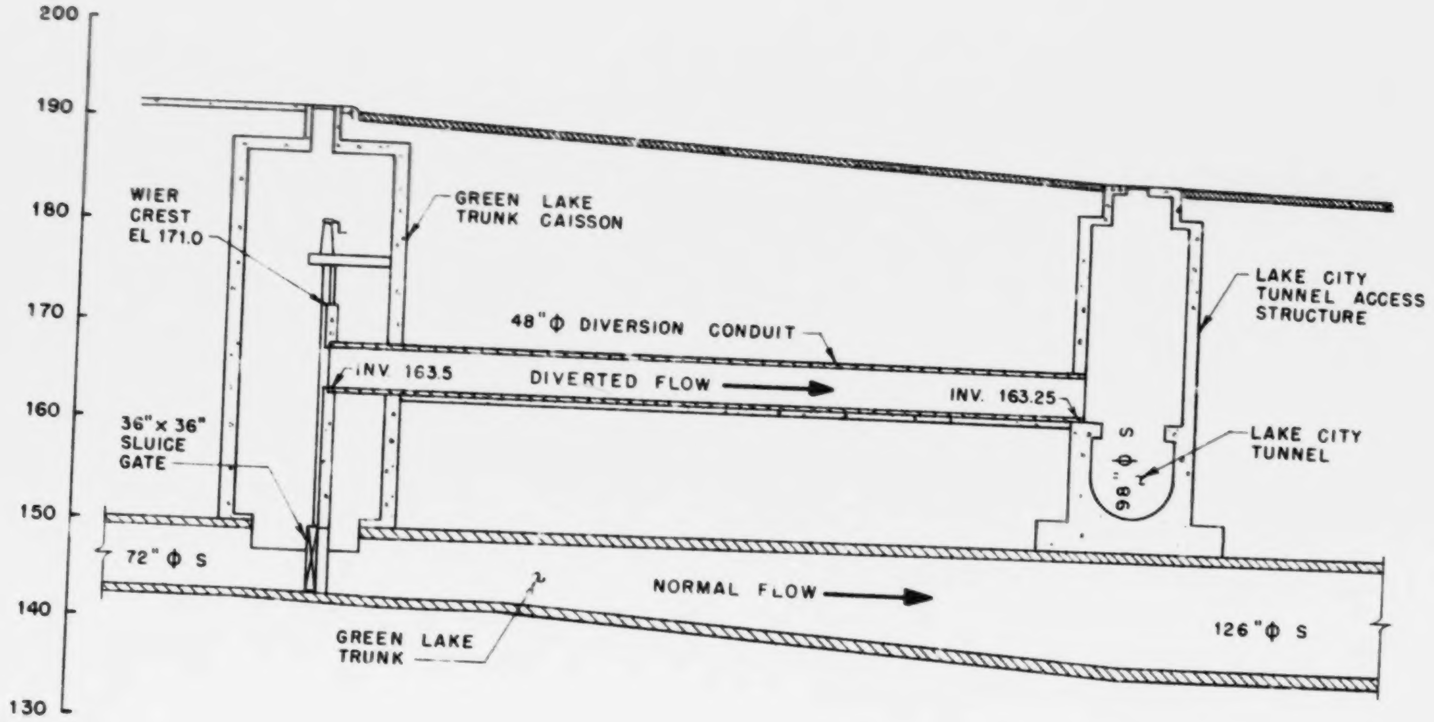

200
190
180
170
160
150
140
130
WIER CREST EL 171.0
GREEN LAKE TRUNK CAISSON
36"x 36" SLUICE GATE
72" Φ S
48" Φ DIVERSION CONDUIT
INV. 163.5
DIVERTED FLOW
INV. 163.25
LAKE CITY TUNNEL ACCESS STRUCTURE
LAKE CITY TUNNEL
98" Φ S
NORMAL FLOW
GREEN LAKE TRUNK
126" Φ S

FIGURE 58
GREEN LAKE TRUNK SEWER
DIVERSION STRUCTURE
PROFILE

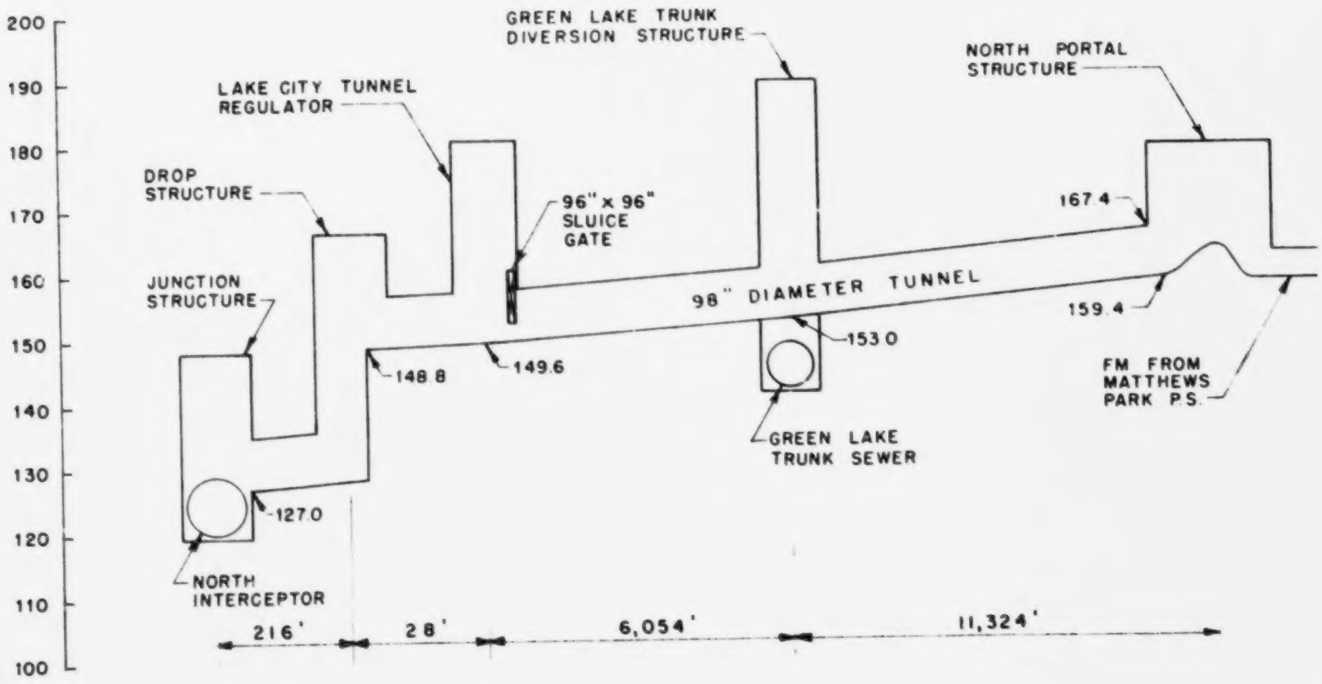

GREEN LAKE TRUNK DIVERSION STRUCTURE
NORTH PORTAL STRUCTURE
LAKE CITY TUNNEL REGULATOR
DROP STRUCTURE
96" x 96" SLUICE GATE
167.4
JUNCTION STRUCTURE
98" DIAMETER TUNNEL
159.4
153.0
148.8
149.6
FM FROM MATTHEWS PARK P.S.
GREEN LAKE TRUNK SEWER
127.0
NORTH INTERCEPTOR
216'
28'
6,054'
11,324'
200
190
180
170
160
150
140
130
120
110
100

FIGURE 59

LAKE CITY TUNNEL SYSTEM PPOFILE

Operation Criteria

The Lake City tunnel regulator and the Matthews Park pumping station provide storage during periods of high flow in the Lake City tunnel system and upstream of the Matthews Park station. CATAD control of the Matthews Park pumping station is described in Section V. CATAD controls the regulator station as a directly operated gate, also described in Section V, with the following exception. When the regulator station is returned to local/automatic control, the gate is programmed to open fully and remain. Controls are adjusted to provide safe return to the fully-opened position without hydraulic overload to the drop structure downstream of the regulator.

When the Green Lake trunk was diverted to the Lake City tunnel, CATAD console operators were appraised of the expected flow increases. They were advised to expect flows in the neighborhood of 140 mgd and to maintain a storage elevation no greater than 161 feet, upstream of the regulator gate. They were also requested to limit gate flow under controlled operating conditions to 200 cfs.

Hydraulic Transients

Continuous water stage recorder charts monitoring the Green Lake system during the diversion to the Lake City tunnel indicated that on several occasions transient conditions occurred in the interconnected systems. Ten incidents on separate dates can be inferred from the charts. The chart records indicate hydraulic transients of considerable force and duration with repetitive and periodic characteristics. One overflow incident at the north portal was not accompanied by indications of transients on the diversion chart. Probable causes of surging and oscillations of the water surface elevation include: exceeding recommended limitations of storage elevation in the Lake City tunnel; a closed or virtually-closed gate at the downstream end of the tunnel; a substantial volume of liquid diverted to the tunnel from the Green Lake system, probably at widely-varying large rates of flow; and inadvertent loss of pumping rate computer control at the Matthews Park pumping station. These severe incidents each occurred during periods of protracted storm conditions.

Available data tends to correlate the events although there are many discrepancies. The compressed time frame of the diversion structure water stage recorder chart and inaccurate hour setting of the charts present difficulties. Operational records on the Matthews Park pumping station are incomplete. In some instances, only hourly logs were available for review.

Conclusions

It now appears that the principal factors contributing to the transients in the system were significant changes in the rate of flow directed to the tunnel from the pumping station, the Green Lake system, or both concurrently without proper regard to remaining storage volume. The potential for significant surge or other transient phenomena is less when the pumping station is the single major source of flow.

Gate movements affect velocity change, but are much less likely to induce transient conditions. In a full conduit, the rate of gate movement is such that a pressure wave generated at the gate requires about 9½ seconds to travel the length of the conduit and return to the gate. In a partially-filled conduit, a wave-reflected free-water surface is closer to the gate, reducing the round trip distance and time interval. Gate opening area change either in the opening or closing direction possible in approximately 10 seconds, would normally effect little water velocity change in the conduit upstream of the gate. Some pressure change will occur.

Lack of gate movement control, particularly in the opening direction, significantly affects flow conditions at the drop structure entrance. Hydraulic model tests of the drop structure and approach channel determined the discharge characteristics with and without a gate installed in the approach channel. With storage in the conduit, discharge under the partially-opened gate is at a very high velocity, and the water prism assumes a position of severe superelevation at its contact with the chamber spiral boundary. Extreme turbulence is present. Tests indicated that a gate opening and head relation should limit discharge rate to about 200 cubic feet per second through a partially-opened gate. Tests without a gate installed (equivalent to the gate in the fully-opened position) under uninterrupted flow conditions and without storage indicate that normal progressive discharge rate changes have no appreciable effect. Conditions are very stable and the performance effective up to a discharge rate twice the capacity of the tunnel.

Pump Cavitation

Artificial pump speed versus wet well limitations were added to computer command programming in the fall of 1972 after an operator's inadvertent entry of an erroneous pump speed request caused extreme pump cavitation at one of the pumping stations. Automatic lockouts provided in the control system to override the CATAD controls on low and high wet well conditions were not sufficient to prevent the cavitation.

To better understand the causes of the cavitation problem, a general description of the pumping station flow control system and the selection of the pumping unit follows. After initial flows in the sewer at the station site and the ultimate flows to be handled by the station are determined, the sewer is sized to maintain a minimum velocity of two feet per second. Once the pipe diameter and gradient of the station influent sewer are determined, velocity depth and quantity depth relationships for all depths of flows are known. These relationships are graphically represented as curves "A" and "B" in Figure 60. They are valid as long as a free-flowing regime is maintained in the pipeline. It is impossible to strictly maintain this theoretical relationship, but it is sufficient to assume that pump capacity varies directly with speed. This is assuming three pumping units of similar characteristics are required to accommodate the maximum flow conditions at the station, and the wet well pumping program would be as shown in Figure 60.

Pump purchase specifications should include the net positive suction head (NPSH) available for the pump along with the other operating criteria. The NPSH available is a function of the system in which the pumps operate and can be calculated for each installation. The station pump flow control curve sets one of the criteria for calculating the NPSH. The available NPSH should be greater than the required NPSH of the pump. When there is insufficient available NPSH, pump cavitation occurs.

Pump command limitations provide that no pump under computer control shall have a speed greater than that allowed a pump in the operating mode 1 (see Figure 60). These limitations provide practical control to prevent pump damage, but enable CATAD pumping control programs to use the storage available in the interceptors. Actual operating data on one station served by a 102-inch interceptor allows a storage volume greater than 2½ million gallons to be developed through CATAD programs which draw the influent interceptor below normal flow depth ranges.

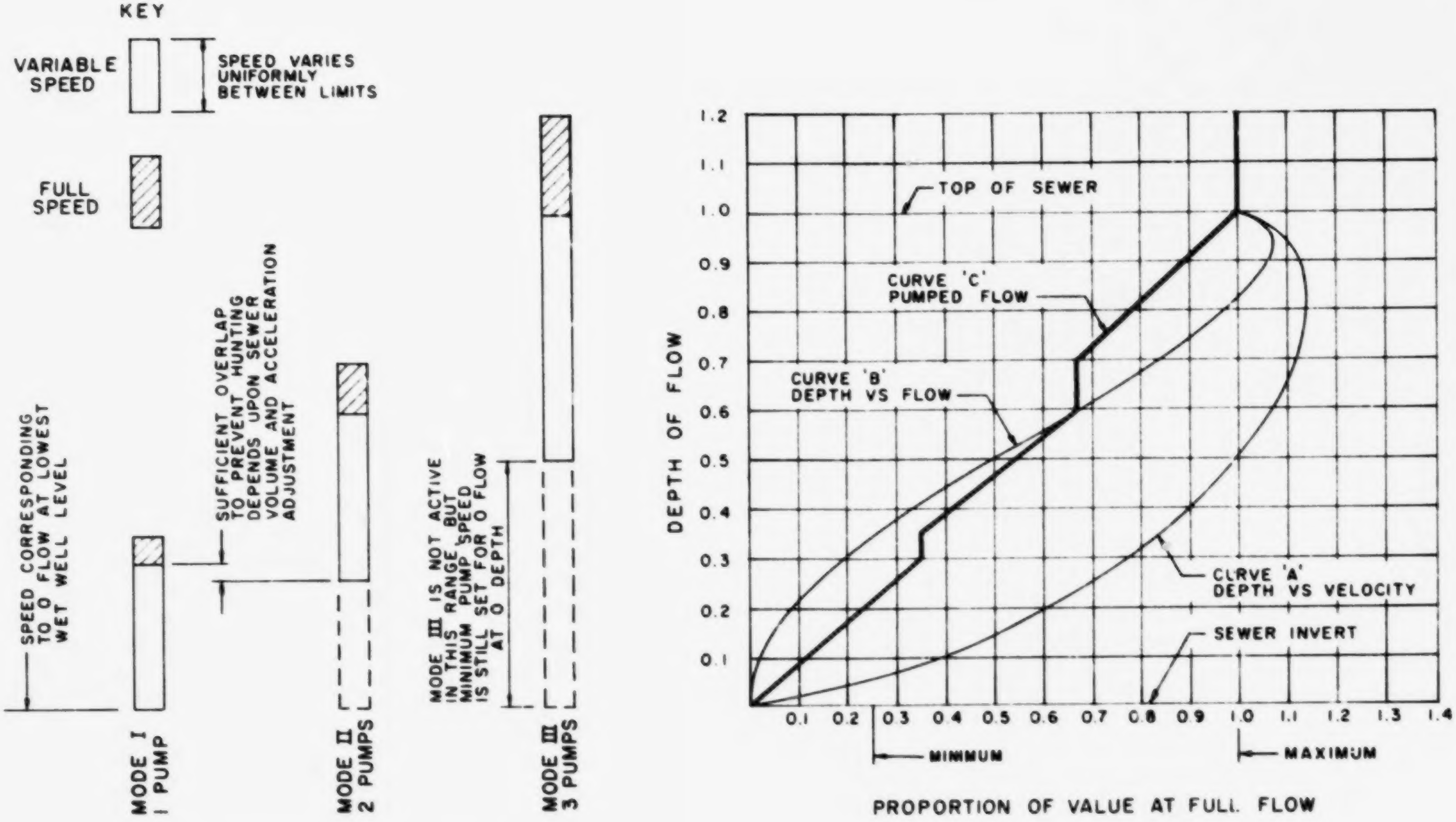
FIELD EQUIPMENT CALIBRATIONS

Force Main Calibration

Force main calibration at selected Metro pumping stations was undertaken to develop a computer formula for accurate indication of flow at selected locations. This calibration effort also provides a reference index for checking force main deterioration and deterioration of pump impellers in the pumping stations.

The work was divided into three basic areas:

1. Field Work
2. Computations
3. Permanent Equipment Selection



WET LEVEL CONTROL PROGRAM

FLOW AND VELOCITY FOR A SEWER FLOWING PART - FULL

FIGURE 60

WELL LEVEL CONTROL FOR VARIABLE SPEED PUMPING

Field work included developing a method for testing of force mains; developing equipment for force main calibration; and running actual field tests. Computations involved test data review and fitting to fixed mathematical formuli; and selecting the best formula for the computer program. Equipment selection involved selecting transmission equipment, installing the equipment in the field and calibrating permanent equipment at each station.

Force main calibration test stations were chosen with two objectives: first, the service areas should provide representative flows so that their results could be interpreted to indicate flows in other areas of the system; secondly, stations such as the Interbay station, could be used to check flow calculations and backwater curves run through a large section of interceptors. Stations with force main transmitters are listed in Table 16.

Table 16. FORCE MAIN CALIBRATION STATIONS

West Point System	Renton System
Kenmore	Juanita Hts.
Matthews Park	Kirkland
30th N.E.	Bellevue
Interbay	Sweyolocken
	N. Mercer Isl.
	S. Mercer Isl.

The Wilburton and Heathfield pumping stations were included in the original list.

The Wilburton station was deleted when analysis showed unusable force main pressures. This force main discharges into the middle of the Wilburton siphon, causing a varying dynamic head on the force main which cannot be calibrated in proportion to the flow through the station. The Heathfield station was deleted after initial calibration efforts. Preliminary analysis of station data obtained indicated up to 30 percent difference in the repeatability of calibration runs. Additional runs after calibrating equipment was rechecked verified the discrepancies. It is believed the vertical alignment of the force mains in this station creates a partial air block in the force main line, causing an uncalculable restriction in the main. Since this station is scheduled to be replaced within ten years, it was decided to eliminate the station and not try to correct the force main problems. Renton system maintenance personnel reported there are no problems maintaining flows for the area that the station services.

Various force main methods were reviewed including: the use of flumes or weirs; total count method using radioactive isotopes; and the salt velocity method. Flumes and weirs were discarded because of capacity problems; the ratio of minimum to peak flows; and installation problems at a location which could isolate the flow of the pumping station. Force main discharge locations into the receiving interceptors did not readily lend themselves to installing flumes or weirs.

The best method might be the radioisotope total count method. However, the Municipality's stations are designed with pumping capacities in excess of today's flows. The availability of water for testing a station is a problem. Low flow rates can be calibrated by storing in sewers upstream of the station. Occasionally, an extremely heavy rain in the service area produces an individual station flow close to present connected capacity. Calibration of high flow rates must be done during periods of storm flows. Radio-active isotope use requires that a radiological safety officer be available during the test period. Since some test schedules depended on the weather, a method utilizing Municipality personnel would avoid keeping a radiological safety officer on call.

The method selected is a variation of the "Salt Velocity Method of Water Measurement" by C. M. Allen and E. A. Taylor. (31)

The first force main calibration tests were made at the Kirkland station. Instrumentation, primarily pneumatic, was borrowed from the instrument shops to test the validity of the proposed program. Three calibrated test gages were purchased. These tests showed the need for more accurate equipment and additional instrumentation was obtained.

Conclusion and Recommendation

The force main calibration program provided the CATAD system with a convenient method of developing primary flow meters in existing pumping stations where flow meters were not provided in the original installations. The program developed calibration methods for the force mains and mathematical formuli for computer programs. Because of the significance of this newly developed method of flow analysis, and possible applications in other cities, detailed description of the methods and equipment are described in Appendix I.

The following procedures are recommended:

1. Force main calibration should be rechecked in a continuing program. Each force main should be recalibrated at least once every five years.

2. Force main pressure transmitter range elements should be changed to fit the actual operating ranges found within the stations. The unit originally installed at the Kenmore station has a minimum span of approximately 40 psig. Units with a minimum span of approximately 5 psig were substituted.

3. Flow meters should be considered for variable speed pump controls. If practical, flow meters, rather than force main pressures, should be used to provide remote flow indication through the CATAD system.

Pump Speed Calibration

Accurate representation pump speed proved difficult. Attempts to calibrate pump speeds using a standard strobe light to stop motion on some particular point of the pump shaft showed that each technician came up with a different set of values, varying 10 percent or greater. Even least squares analysis of the test data produced unacceptable values. When this data reached the CATAD console, the results did not correspond to other known station data, generating the many invalid pump speed alarms.

The pump speed analog value is generated by a d-c tachometer generator coupled to the pump shaft, producing a known voltage per rpm (see Figure 61). A pump speed indicator is located on the pump station control panel. The CATAD equipment parallels a dropping resistor and a voltage-to-current converter with the local speed indicator to provide a signal to the TCU. The resistance is adjusted to produce the desired 2-10 volt output signal in the TCU. Most of the station pumps are driven by electric motors and the

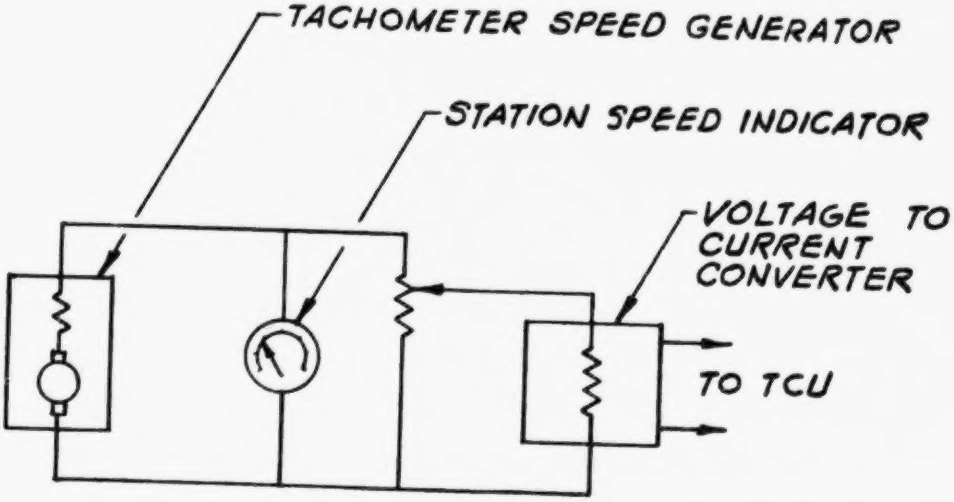


FIGURE 61

PUMP SPEED ANALOG CIRCUIT

10-volt level adjustment is slightly greater than the synchronous speed of the motor. Calibration problems of the pump speed analog signal were discussed with the Metro electrical design department. After a search of the literature of equipment available, they decided that no equipment on the market could provide the desired pump speed calibration accuracy. They developed a retroreflective photosensor head which, with a frequency counter, provides an accurate representation of pump speed. Equipment used for pump speed calibration is listed in Table 17.

Table 17. PUMP SPEED CALIBRATION EQUIPMENT

Component	Characteristics
Computing Counter	Monsanto Model 107A
Retroreflective Photo Sensor (Schematic in Appendix C)	Metro Electrical Engineering Department Constructed
Tripod	Heavy-Duty Photographer's Tripod with Tilting Head

The computing counter was selected because its ability to indicate rpm with an update at least every four seconds in the low frequency range of 100-500 rpm. The device can also be used as a frequency meter for other electronic work. The retroreflective photo sensor was job-built by the Metro electrical engineering department to specifically meet the pump speed calibration need. The unit was miniaturized so that it could be readily focused through pump frame handholes. Final size is approximately 1 and 3/4 inches high by 2 and 1/4 inches wide by 4 and 1/4 inches long. The unit contains a source light and photoelectric cell to pick up the reflected light which indicates frequency as well as the electronics required to give the frequency impulse for transmission to the computing counter. The electronics are driven by a 9-volt battery, and the source light is driven by a 3-volt battery, providing 70 to 80 hours of usage. The unit operates successfully up to approximately four inches from the shaft. A tripod is used to mount the sensor and hold it steady adjacent to the equipment. An electrical conduit extension shaft permits the tripod to suspend the sensor over larger pump casings. Coaxial cable connects the sensor to the counter.

The pump shaft is reconditioned with a band of black paint sprayed onto the rotating shaft. The pump is stopped and a longitudinal white stripe of tape placed on the shaft to provide a reflective surface. The sensor is mounted adjacent to the shaft and connected by cables to the counter in the pump control room. The pump is started, and the counter read while the pump is held in various steady-state conditions.

The test data was then subjected to solution by the least-squares analysis. A typical calibration table prepared for a station is shown in Table 18. CATAD console checks on various stations with the counter in place has shown less than approximately two percent error in pump speed versus actual speed read at the station with the proper values entered into the computer program.

The pump speed retroreflective photosensor and computing counter are a valuable maintenance aid for the Metro system maintenance department. It has been well received by the mechanics working within the system. Municipality maintenance forces have built a second sensor and acquired a second computing counter for regular pump speed calibration.

A photograph of the calibrating equipment in use is shown on Figure 62.

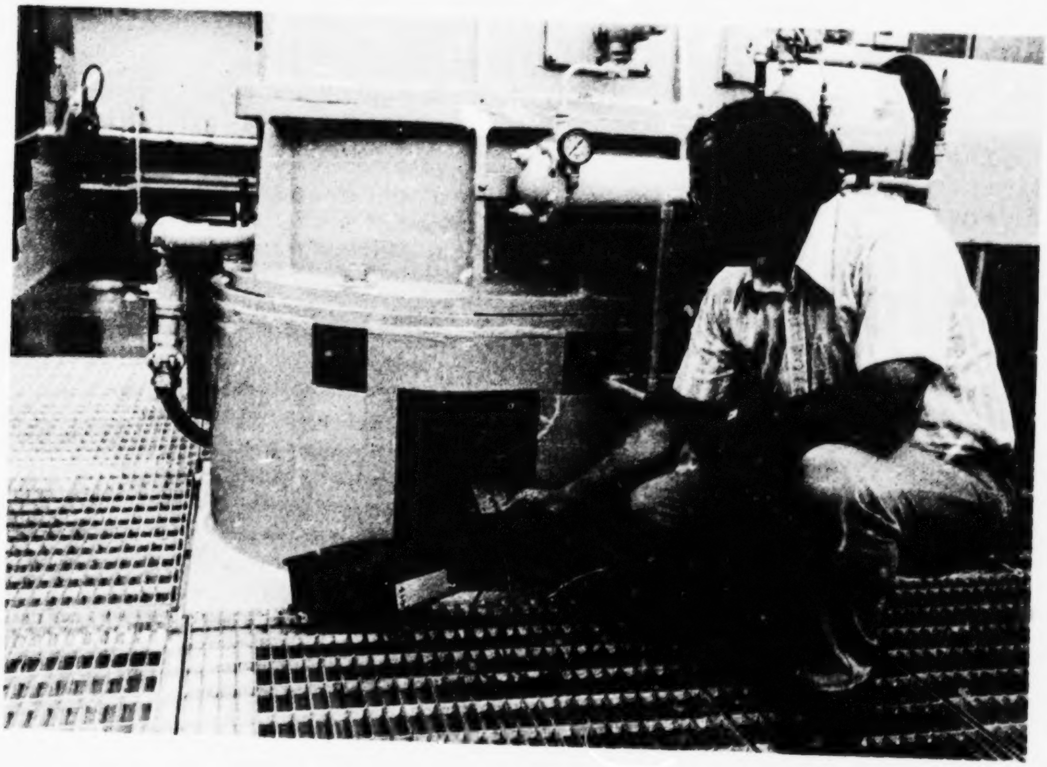


FIGURE 62

CALIBRATION EQUIPMENT IN USE

Table 18. PUMP SPEED CALIBRATION DATA

Pump No:	1	Pump No:	2	Pump No.:	3
Date:	7/11/72	Date:	7/11/72	Date:	7/11/72
V/I No.:	V/I 111C	V/I No.:	V/I 112C	V/I No.:	V/I 113C
Pin No.:	5 G/H	Pin No.:	5 J/K	Pin No.:	5 L/M
Analog No.:	7	Analog No.:	10	Analog No.:	11
Volts	RPM	Volts	RPM	Volts	RPM
3.63	407.63	3.58	400.24	3.54	400.34
4.46	593.43	4.50	601.85	3.76	450.06
5.45	809.49	5.41	800.03	3.99	500.94
6.35	1009.4	6.33	1000.5	4.46	600.74
7.11	1175.6	7.14	1177.4	5.36	800.52
7.78	1322.9	9.75	1744.0	6.27	1000.04
8.70	1525.5	8.54	1483.4	7.05	1174.5
9.63	1730.5	7.43	1243.1	7.07	1177.0
				7.36	1241.0
		9.61	1738.9	7.91	1365.0
		9.61	1741.0	8.62	1520.0
Minimum Pumping Speed	600 RPM	Minimum Pumping Speed	600 RPM	Minimum Pumping Speed	600 RPM
Maximum Pumping Speed	1745 RPM	Maximum Pumping Speed	1745 RPM	Maximum Pumping Speed	1745 RPM

Level Sensing

Difficulty providing reliable water levels as an indication of sewage flow appeared early in the calibration of equipment feeding the CATAD system. Some sewage flows appeared to be going uphill and tide levels at stations a few miles apart appeared to differ by two feet or more! When the stations were originally constructed, no attempt was made to adjust the controls of one station relative to the levels in any other station; all stations were calibrated on a "stand alone" basis. This complicated indication of water surface profiles required for CATAD system operation.

The normal Metro system level sensor is a pneumatic bubbler located in the interceptor or trunk sewer with back pressure read by a differential pressure transmitter. Transmitters have approximately 300 inches maximum range with elevation and suppression of transmitter zero and adjustable span. In most instances, level indication locations within the system were sufficient to provide the needed water surface indication. Pre-CATAD level sensor adjustment had generally been done with little care. Adjustment within 10 percent of desired values provided adequate station operation. Adjustment and calibration used inexpensive gages of questionable accuracy, which did not provide an accurate indication of water surface profiles. Sensor calibration for the CATAD system was undertaken to provide accurate indications of water surface profiles to a known datum base. Most stations are relatively new and good as-built drawings were available to provide sufficient information relative to bubbler tube elevations in the trunks and interceptors. In a few instances, reference elevations were brought in by survey crews. The primary level sensor calibration equipment was a Wallace and Tiernan series 65-100 portable pneumatic calibrator and a shop-fabricated hook gage for accurate determination of water surfaces at the time of calibration. All sensors were calibrated to a fixed datum base; calibration ranges were established; and sensors are now regularly calibrated to this criteria.

FIELD PROBLEMS

Gate Position Study

The gate position study was undertaken after universally poor gate position transmitter resolution was found in the gear-driven gate operators, as discussed in Section V. Modifications of the gear train final elements improved the reading somewhat, but this remains one of the most critical readings in the system. The manufacturer's position transmitter drive was not intended for high resolution tracking.

The Municipality began a search for a better transmitter and system. One unit obtained for inspection operates on a tape reel principle similar to the units used on some of Metro's hydraulic gates. This model has a multi-turn potentiometer with an accuracy about 1/100 percent of full range. No field testing of the unit has been attempted. Such a unit, although accurate, may not stand the severe environment of the gate operator rooms. It does not carry the UL or RM label for application in hazardous areas. Presently available models would require excitation by an intrinsically safe system or would require special mounting within the explosion proof gate operator housing.

Explosion Hazard Study

The explosion hazard alarm is monitored by the CATAD system to make Metro immediately aware of the condition. Before the CATAD installation this alarm was grouped with other priority 1 alarms on Metro's telemetry system. CATAD system analog transmission capability allows the degree of explosive hazard to be transmitted as an analog signal along with the alarm status.

The standard alarm monitor units provide a proportional voltage output for recorder monitoring. This signal is amplified and transmitted to the TCU as an analog point.

The explosive gas hazard must be monitored because the Seattle portion of the Metro system in particular is subject to gasoline and chemical dumps. Gasoline usually comes from gasoline truck accidents (overturns) which the fire department washes down the storm sewers. The vapors from these spills as well as from illegal industrial solvent dumping present an extreme hazard in manholes and stations downstream from the point of entry. Little methane hazard is present in the Seattle system because of the relatively short sewage retention time.

Transmitting the station explosion hazard alarm only would provide adequate early warning that some particular preset vapor concentration had been reached in a station wet well. Transmitting the analog signal permits the console operator to assess the severity of the problem and its rate of change. This information helps to decide whether an operator should be dispatched to the site and whether the treatment plant should prepare for diversion or retention of the impending hazardous inflow.

Metro's operations group noted monitoring equipment problems over the years (particularly with sensors) and undertook an investigation of equipment on the market prior to installation of monitors in selected stations not presently equipped. The study brought to light information regarding explosive gas monitoring that is not available in the literature.

The degree of explosion hazard is a qualitative measurement based on lower explosive limit (L.E.L.). This measurement varies widely with the type of gas and is a measure of the concentration of a particular flammable gas under controlled conditions. In a sewer system, the type of hazardous gas is not predictable and the surrounding atmosphere is not normal. At best, the reading is a relative value. Metro had followed the manufacturer's procedure and calibrated the monitor heads on methane in the past. This calibration method reduces the monitor output signal for gasoline by 40 to 50 percent of full scale L.E.L. reading. The monitor should be calibrated using hexane or heptane gases. As a compromise, heads were calibrated on a 2 percent methane gas and transmitter gain set for 100 percent L.E.L., which resulted in a normalization of the calibration point to equivalent propane. Propane is not used for calibration because it is unavailable in the air dilutions required.

The investigation found that some heads installed in exhaust air ducts were totally ineffective because the high volumetric flows in these ducts dilute the vapors. A study is underway to relocate and increase the number of sensing points and to locate the sensor heads closer to the sewage surface. A contract will be let soon to install equipment in selected stations in order to follow the flow of hazardous discharges through the system, providing an accurate measure of the arrival time of the hazardous material to the West Point plant where it must be contained or bypassed.

Dexter Avenue Regulator Station

The Dexter Avenue regulator station (see Figure 63) was constructed on the Central Interceptor in 1971 permitting storage of combined wastewater in the 84-inch sewer upstream of the station to minimize overflows to Lake Union from a side channel overflow structure immediately downstream of the station.

The benefits of the Dexter Avenue regulator station were described in "Maximizing Storage in Combined Sewer Systems." (6) During a 1969 monitoring period prior to construction of the regulator station, overflows to Lake Union occurred on eight separate occasions. Analysis showed that the regulator station would have eliminated all but one of these overflows.

The regulator station was provided with a modulating regulator gate and an emergency bypass gate as shown earlier in Figure 5D. Regulator gate control modes are shown in Figure 64. Under dry weather flow conditions (Mode 1) the regulator gate lip is set at a fixed elevation above the sewer invert. During moderate storms when flow exceeds the capacity of the 48-inch sewer downstream of the station (Mode 2) the regulator modulates to store wastewater upstream and release a quantity of wastewater upstream and release a quantity of wastewater equal to the downstream sewer capacity. Under peak storm water conditions when the upstream storage capacity is exceeded (Mode 3) the gate modulates to maintain storage at the maximum level to minimize overflows. The bypass gate is provided with a tripping mechanism backed up by an electronic tripping device. Once activated, the bypass gate moves to a fully open position and remains open until it is manually reset.

Under peak storm water inflow conditions (Mode 3) the station operates under the following setpoint elevation conditions:

Bypass gate trip---------------1
Regulator gate open------------2
Opening neutral-----------3
Closing neutral------------4
Regulator gate closed---------5

Dead
band
width

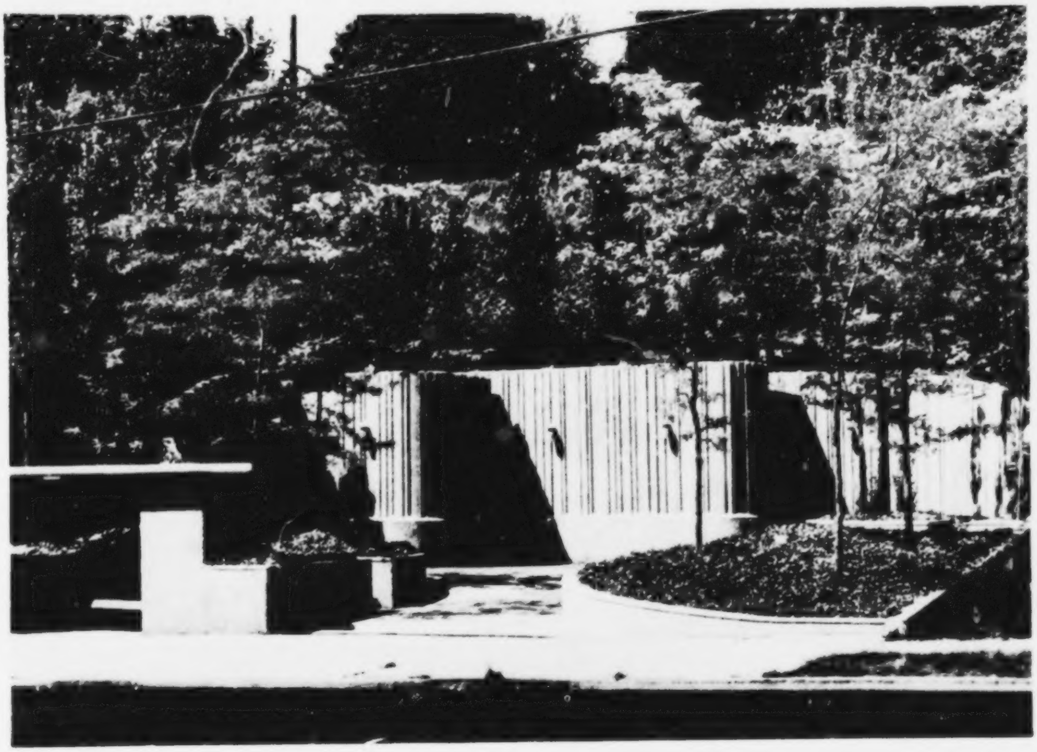
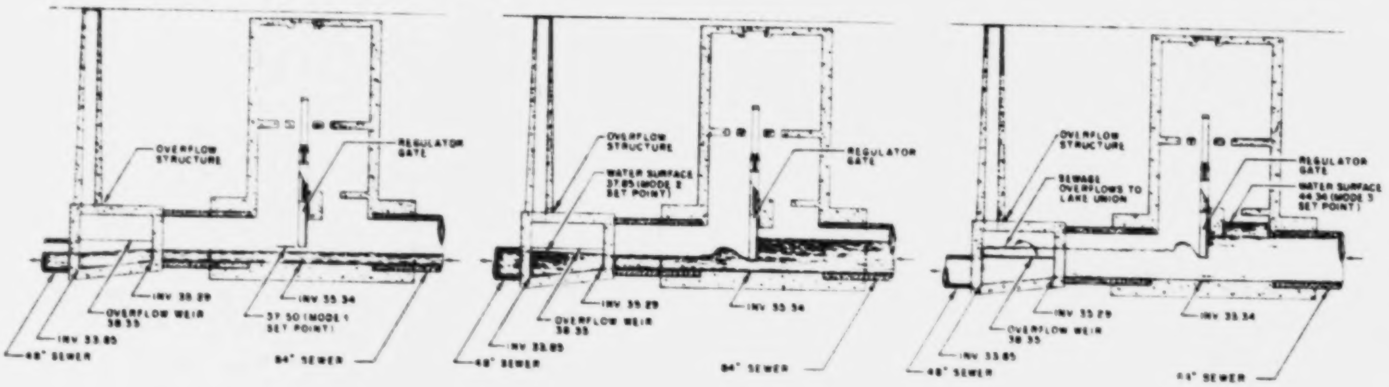


FIGURE 63

DEXTER AVENUE REGULATOR STATION


OVERFLOW STRUCTURE
REGULATOR GATE
INV 35.29
INV 35.34
OVERFLOW WEIR 38.35
37.50 (MODE 1 SET POINT)
INV 33.85
48" SEWER
84" SEWER
OVERFLOW STRUCTURE
WATER SURFACE 37.85 (MODE 2 SET POINT)
REGULATOR GATE
INV 35.29
OVERFLOW WEIR 38.35
INV 35.34
INV 33.85
48" SEWER
84" SEWER
OVERFLOW STRUCTURE
SEWAGE OVERFLOWS TO LAKE UNION
REGULATOR GATE
WATER SURFACE 44.34 (MODE 3 SET POINT)
INV 35.29
INV 35.34
OVERFLOW WEIR 38.35
INV 33.85
48" SEWER
84" SEWER

CONTROL MODE	MODE 1	MODE 2	MODE 3
FLOW CONDITION	INFLOW IS LESS THAN CAPACITY OF THE DOWNSTREAM SEWER	INFLOW IS GREATER THAN CAPACITY OF DOWNSTREAM SEWER, STORAGE VOLUME AVAILABLE UPSTREAM	INFLOW IS GREATER THAN CAPACITY OF DOWNSTREAM SEWER. THE UPSTREAM SEWER IS SURCHARGED TO ELEVATION 44.34 (2 FEET ABOVE CROWN)
REGULATOR GATE CONTROL	REGULATOR GATE IS HELD TO KEEP THE BOTTOM OF THE GATE LEAF AT ELEVATION 37.50	REGULATOR GATE IS POSITIONED TO MAINTAIN A WATER SURFACE ELEVATION OF 37.85 IN THE OVERFLOW STRUCTURE. EXCESS FLOW IS STORED UPSTREAM OF THE REGULATOR GATE	REGULATOR GATE IS POSITIONED TO MAINTAIN WATER SURFACE UPSTREAM OF GATE AT ELEVATION 44.34. SEWAGE SPILLS OVER WEIR IN OVERFLOW STRUCTURE TO PREVENT FLOODING UPSTREAM

FIGURE 64

REGULATOR GATE CONTROL MODES - DEXTER AVENUE REGULATOR

When the water surface elevation rises to the regulator gate open position (elevation 2), the regulator gate begins to open at a constant speed to release wastewater from storage. The regulator continues to open until the upstream water surface drops to the opening neutral position (elevation 3) at which point the gate motion ceases. Likewise, in Mode 3, the regulator gate begins to close when the upstream water surface drops to the gate close position (elevation 5) and continues to close until the water surface rises to the closing neutral position. The neutral positions may overlap to place the closing neutral position above the opening neutral position. If the upstream water surface rises above the bypass gate trip position (elevation 1), a float mechanically initiates bypass gate opening.

On two known occasions, the bypass gate was inadvertently tripped by high upstream water surface elevation. The resultant surge overflow to the Lake Union outfall backed up in connected storm sewers releasing objectionable combined wastewater on local streets. A study was initiated to determine the cause and to recommend optimum setpoint conditions. The station was visited to determine in-place setpoint conditions. It was discovered that, contrary to initial station design, the regulator gate open setpoint was set at an elevation above the bypass gate trip position. This situation (which was immediately corrected), virtually insured bypass gate opening in Mode 3 conditions.

A computer program was constructed to simulate regulator gate operation under all flow conditions. This program simulated station behavior under various setpoint conditions with a triangular-shaped inflow hydrograph. The program was used to calibrate Mode 3 setpoint conditions to maximize storage while minimizing the possibility of inadvertently opening the bypass gate. The program also tested the effect of bypass gate opening rate on the subsequent rate of overflow into Lake Union. Additional drawings of this regulator and discussion of the simulation program are presented in Appendix J. The successful application of this technique using available background computer time on the real-time computer led to its use for analysis of other difficult hydraulic control situations in the Metro collection system.

SPECIAL MAINTENANCE REQUIREMENTS

The interface boundary between the system assigned to the CATAD contractor's maintenance and that for which Metro assumed full responsibility was carefully chosen. The reason for limiting the contractor's area of responsibility was discussed in Section V under "Design Considerations."

During preparation of the first CATAD interface contract for the Elliott Bay Interceptor, the design engineer suggested that Metro build a simulator to properly check out the stations before acceptance. The number of multi-pin plugs to be checked point-by-point indicated a large possibility of error and excessive engineering time required for checkout. Metro assigned its consultants to provide two units, one for pumping stations and one for regulator stations. Investigation indicated a saving in common equipment and space if a single unit simulated the telemetry control unit (TCU) operation for both regulators and pumping stations. A size limitation was imposed by the necessity to use the simulator in a "package" pumping station (Kenmore) with a manhole cover-type entrance. Portability placed a weight limitation on the unit. The simulator was built with analog indicators and status lights plus command pushbuttons. The unit measures 18 x 20 x 10 inches and weighs about 30 pounds. A reversible legend plate fits over the face of the unit. One side of the flip plate identifies functions for a pumping station and the other side identifies functions for a regulator or outfall station. The internal wiring nomenclature (pin identification) for all receptacles is engraved on the face under the flip plate. Figure 65 shows the simulator in operation.

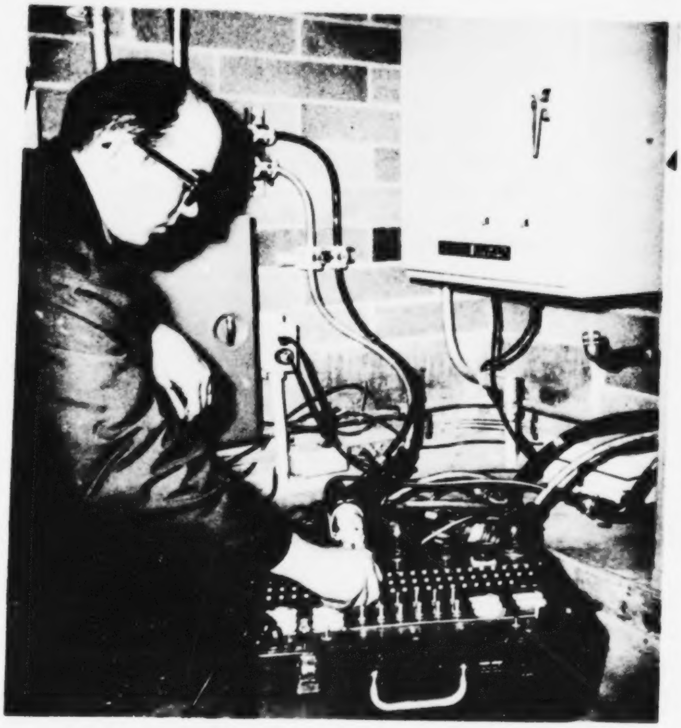


FIGURE 65

METRO TELEMETRY UNIT SIMULATOR

The CATAD contractor, Philco-Ford Company, had build a station simulator providing signals to check the operation of their TCU's and their control system prior to equipment delivery. The manufacturer and Metro realized that the two simulators would be extremely valuable in locating and correcting problems in the remote stations whether on the TCU side of the interface or within Metro's station equipment. Because of the nature of the system, some malfunctions are difficult to trace. A faulty plug or broken wire in the interface connecting cords can be very difficult to find. Separating the two units easily determines whether the problem is on the TCU side or on the station side. This would apply even if one technician were responsible for all system maintenance. Where two different maintenance groups exist, as in the CATAD system, the problem is even more important because each group can be expeditiously freed of the other's problems. The station simulator appears in Figure 66.

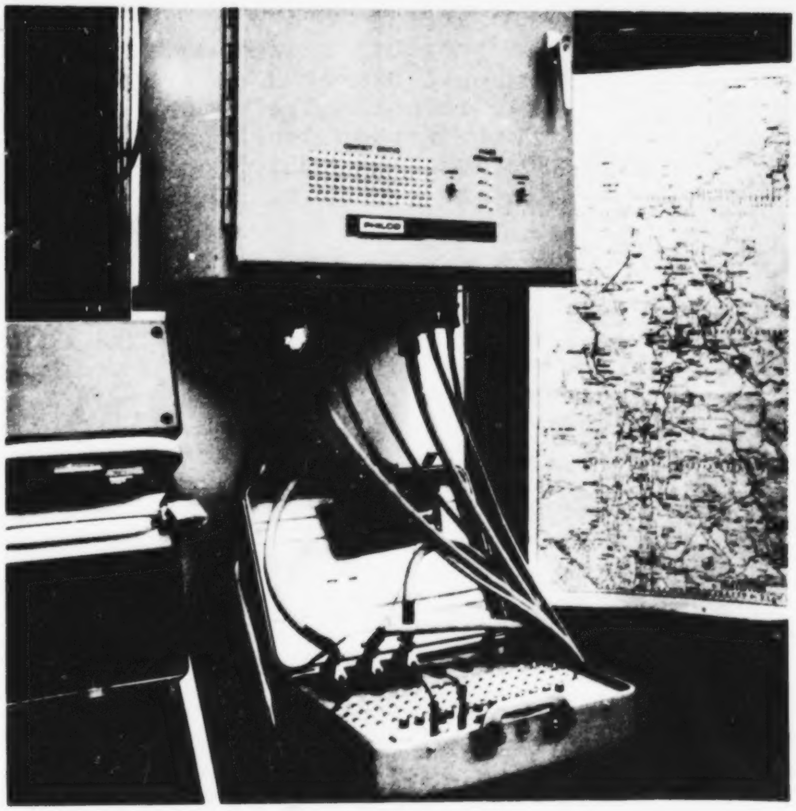


FIGURE 66

CONTRACTOR'S PUMP STATION SIMULATOR

All CATAD stations in Metro's system are pre-checked for proper operation and connection and are operated directly from the simulator prior to TCU connection. All alarm and status points included in each station are checked prior to plugging in the TCU cables.

The simulator detects all errors which might subject expensive solid state TCU input components to damaging voltages due to improper station equipment installation.

OPERATIONAL CONSTRAINTS

As pointed out by Grigg (11) and Tucker (32), local and municipal sewerage agencies have great difficulty developing a fully controlled sewage collection system because of many factors which tend to constrain development. Metro encountered many of these road-blocks, but a dedicated, hardcore group of staff and operating personnel continued with the project, believing in the goals of the control system. These people hammered at the multitude of problems to forge a workable, if not quite successful, control system. The remainder of this section describes significant constraints which were overcome and those which continue to limit effort.

Sewer System Layout

West Point Maximum Flow - CATAD system control is applied to the portion of the Metro area which routes sewage to the West Point Treatment Plant. Since the West Point Plant must process all sewage added to the interceptor network by CATAD regulator stations, the regulators must not divert a total flow which exceeds treatment plant capacity. Maximum treatment plant capacity is dictated by design and operational constraints. Design hydraulic capacity of the plant is approximately 325 mgd, but a more workable flow of 250 mgd is normally considered maximum. Operating conditions could decrease the maximum plant capacity. Emergency or preventive maintenance might require that a primary sedimentation tank be removed from service, reducing plant capacity.

The treatment plant maximum flow limitation must be evaluated by the CATAD console operator when the system is in supervisory control mode. The automatic control system handles the limitation by providing maximum flow data to the control program through a keyboard entry from the central or West Point operator's console. The maximum flow restriction at the West Point Treatment Plant rarely has an adverse effect on CATAD system operation. The designed maximum plant capacity is sufficient to handle a normal balance of wet weather flow from the interceptors. An unusual condition might exceed plant capacity, but this would be very infrequent.

Preventive maintenance which would adversely affect plant flow can often be scheduled for dry weather periods. This requires coordination between plant operations scheduling and the control system supervisors. This situation is not an insurmountable obstacle. The only situation which might have serious adverse effect on the CATAD system through limitation of plant flows is failure of some piece of plant machinery which makes a portion of the plant unusable. Normal plant maintenance is oriented to minimizing such problems. A good plant maintenance program controls the problem.

Interbay Pumping Station - Flow reaching the West Point Treatment Plant travels one of two possible routes. Flow from the southern collection area must pass through the Interbay pumping station; from the north, flow must pass through the Fremont Siphon (see Figure 67). Maximum Interbay pumping station capacity is approximately 120 mgd. This limitation is often a key factor in determining control for storm conditions. Even though the West Point Treatment Plant may not be handling its full capacity, it could be necessary to initiate a storage plan at Elliott Bay regulator stations since Elliott Bay Interceptor flow has reached the maximum for the Interbay station.

Fremont Siphon - The Fremont Siphon flow limitation is similar to the Interbay flow limitation. The Fremont Siphon limits flow from the northerly area of the system. The siphon's maximum flow is approximately 168 mgd. Greater flow would cause overflow into the Lake Washington Ship Canal, an important fresh water body. Freshwater overflow avoidance has high priority. Thus, a storage scheme must often be implemented upstream of the Fremont Siphon to regulate flow at the siphon itself.

Flow limitation conditions at Interbay or the Fremont Siphon may occur independently of a maximum flow restriction at the West Point Treatment Plant. A heavy, localized storm involving only the north area or only the south area might exceed the capacity of the appropriate station without reaching the treatment plant limits.

Flow Regulation of the North Area - The northern portion of the CATAD control area is dominated by pumping stations. Only one regulator station is now operating. Future plans include four more storage regulators along the North Interceptor (33, 12). The existing regulator station, which controls the Lake City Tunnel, provides a large storage volume for flow coming from the most northerly parts of the system. A second major storage volume is available upstream of the Matthews Park pump station which serves the same drainage area as the Lake City Tunnel Regulator. The rest of the north area is either controlled by pumping stations with very small storage volumes or does not include CATAD control stations. Thus very little control can be exercised over a relatively large percentage of the North Area flow. The Lake City

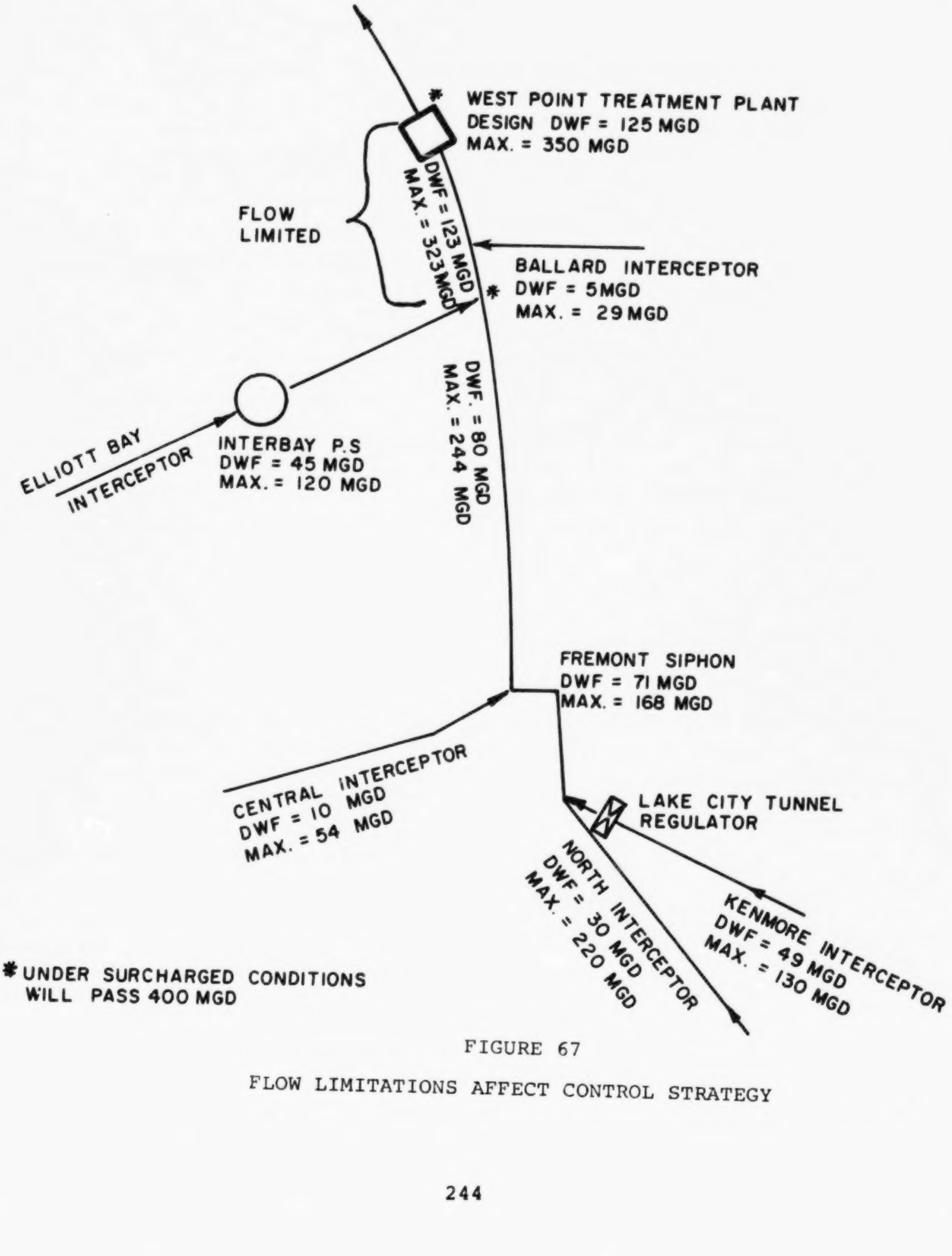

* WEST POINT TREATMENT PLANT
DESIGN DWF = 125 MGD
MAX. = 350 MGD
FLOW LIMITED
DWF = 123 MGD
MAX. = 323 MGD
BALLARD INTERCEPTOR
* DWF = 5 MGD
MAX. = 29 MGD
DWF. = 80 MGD
MAX. = 244 MGD
ELLIOTT BAY
INTERCEPTOR
INTERBAY P.S
DWF = 45 MGD
MAX. = 120 MGD
FREMONT SIPHON
DWF = 71 MGD
MAX. = 168 MGD
CENTRAL INTERCEPTOR
DWF = 10 MGD
MAX. = 54 MGD
LAKE CITY TUNNEL
REGULATOR
NORTH INTERCEPTOR
DWF = 30 MGD
MAX. = 220 MGD
KENMORE INTERCEPTOR
DWF = 49 MGD
MAX. = 130 MGD
* UNDER SURCHARGED CONDITIONS
WILL PASS 400 MGD

FIGURE 67

FLOW LIMITATIONS AFFECT CONTROL STRATEGY

Tunnel and Kenmore Interceptor storage must be used to avoid excessive flows at the Fremont Siphon. Storm situations can exceed their capability to limit the Fremont Siphon flow sufficiently to prevent overflows. Additional stations in the north area will considerably enhance CATAD control capability.

Environmental Conditions

Storm Types - The CATAD control system is used most often during Seattle's winter rainy season. Spring and fall storms require use of the system much less frequently than during the winter. Summer storms, with very few exceptions, are too brief to require special controls. However, overflow control during the summer recreational season is most important.

In addition to the seasonal storm condition variation, different storm types can be identified according to their impact on the CATAD control system. The most difficult is a long duration, general rainfall which is quite common during the winter months. These storms produce nearly continuous rainfall for up to 4 or 5 days. Intensities as high as 0.20 to 0.25 inches per hour are possible, but the average storm intensity is in the area of 0.06 inches per hour. Four to eight hour periods with continued rainfall of 0.10 to 0.15 inches are common in these storms. Such storms put heavy demands on the CATAD system due to both large runoff volume and area-wide involvement. The large runoff volume will tend to maintain high levels in all areas, decreasing the limited storage volumes to zero. The general geographic coverage of the storm precludes selective use of storage in low rainfall areas to ease the impact in other areas. This type of storm is the most likely to cause overflows simply because total hydraulic requirements exceed system capacities.

The more common winter storm lasts from 8 to 24 hours with intensities similar to the longer storm. These storms are also common in the spring and fall, with shorter storms in the spring and longer ones in the fall. These shorter duration rainfall periods display a characteristic common to the Puget Sound area: storm activity, especially during the winter, generally approaches from the southwest. With total rainfall duration of less than one day, the rainfall tends to be less constant even though measurable precipitation may be occurring in all areas. Storm movement across the basin tends to introduce areas of high and low intensity rainfall according to varying patterns of cloud cover and variable land elevations (see Figure 68). The variable nature of this storm type allows the CATAD system to control runoff more effectively since storage can be alternately built up and released as "rainfall segments" of a storm traverse the area. Also, the storm's directional nature helps provide advance warning of its impact by involving outlying areas of the system first as it moves into the area. Data gathered from the first rain-gaging stations to be affected by the rainfall can often give a good indication of area-wide effects.

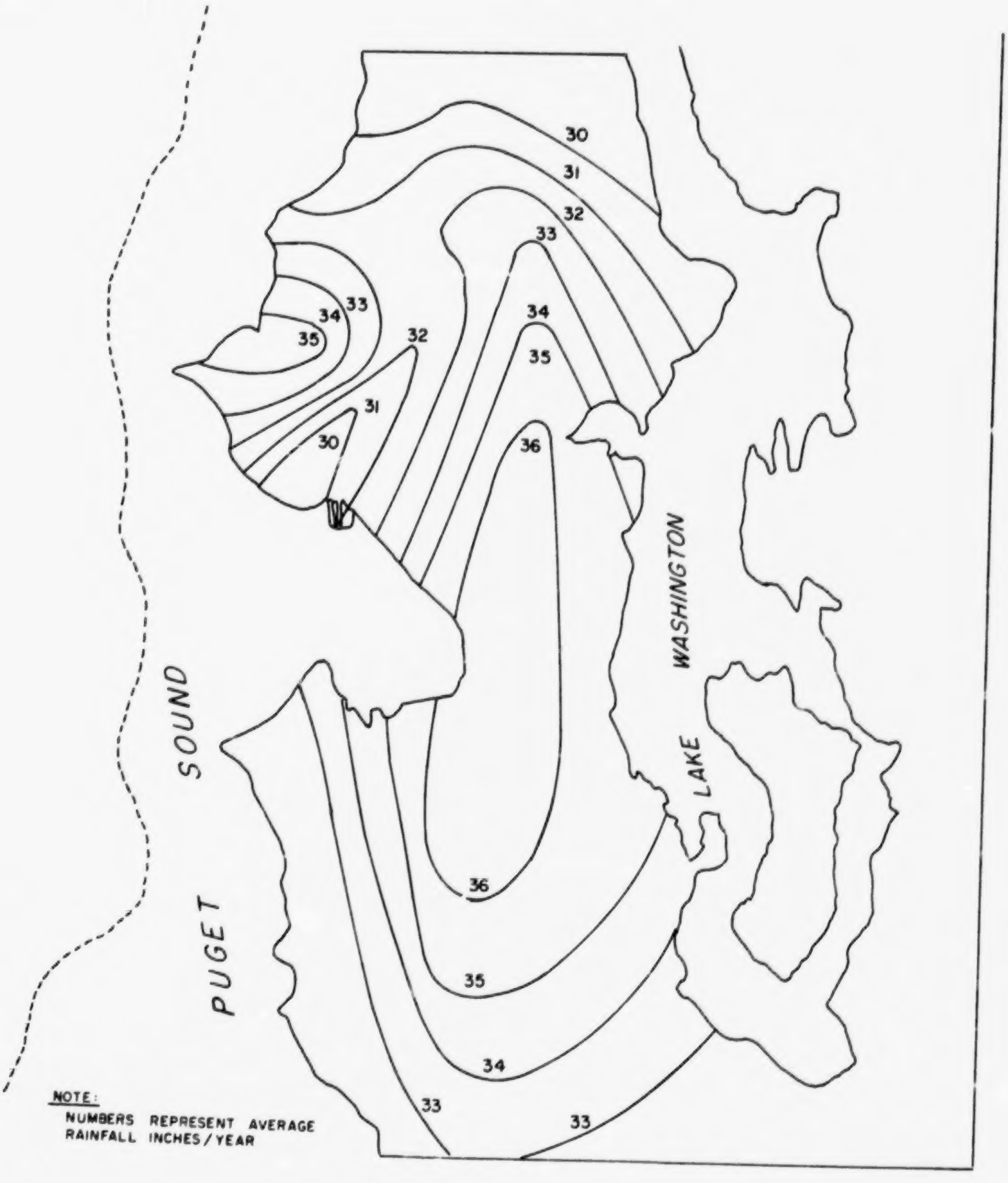

30
31
32
33
34
35
36
33
34
35
32
31
30
36
35
34
33
33
PUGET SOUND
LAKE WASHINGTON
NOTE:
NUMBERS REPRESENT AVERAGE RAINFALL INCHES/YEAR

FIGURE 68

ISOHYETAL MAP OF SEATTLE

Storms up to eight hours long can be expected in any season. Short storms may vary widely in total rainfall volume and maximum intensity. Most storms approach from the usual southwest direction and can be handled by the control system in much the same manner as longer duration storms. From late spring to early fall, an occasional storm may approach from another direction. This usually means a short period of intense rainfall, with little impact on the sewer system. Most short duration storms can be completely contained by the control system with the possible exception of a very high intensity local storm where local trunk and interceptor capacities are overwhelmed by runoff volume.

Tide Effects -- High tides in Elliott Bay and the mouth of the Duwamish River may make it impossible to overflow at selected stations since the tide level is above the trunk sewer level. If an outfall gate were opened, salt water would flow into the outfall increasing the total amount of water in the system. This situation cannot be permitted. Tides high enough to prevent the use of outfalls along Elliott Bay and the Duwamish River are uncommon, but they do occur; most frequently during the winter months. Winter high tides are also aggravated by wind conditions. A southwest wind during a winter storm may build a higher water level along the northeasterly shoreline of Elliott Bay. This condition converts a moderately high tide into one with significant impact on the control system. The original assumption was that it would be extremely uncommon for a tide high enough to limit overflows at many stations to occur simultaneously with a heavy storm requiring many overflows. However, during the winters of 1971-1972 and 1972-1973, there were significant periods (totaling about ten days) when high tides and high storm inflows caused trunk levels to be run higher than normally considered safe. If this condition becomes aggravated in any way, it may become necessary to develop a means of removing excessive storm water volumes from the trunk and interceptor system to prevent flooding low elevation sewer connections.

System Limitations

The CATAD system controls a sewer network which, for the most part, predated CATAD. The sewer network was not designed with computer control in mind. Some sewer network construction and operation factors do not optimally integrate with the CATAD concept. Some of these restrictions may be unavoidable, but others might be avoided by designing for special system requirements. The most favorable condition is to design the sewer system and the control system as a single integrated package; however, the number of locations where this approach is possible is very small since the sewers usually precede the control system. However, for areas using computer control, it is mandatory that sewerage system expansion plans be formulated to take advantage of control technology.

Regulator Stations with Small Storage Capacity -- Three Metro system regulator stations are notable for small storage capacities: Harbor Avenue, West Michigan Street and Denny Way Local. The Harbor Avenue and West Michigan Street regulators control trunk lines with rather severe gradients. In all these stations, the small storage capacity of the trunk lines causes two problems. First, an intense but localized rainfall affecting one of the stations creates runoff conditions which exceed the station capacity and forces overflows regardless of available interceptor space. Secondly, the small storage capacity of the lines makes them useless in lessening the impact of a storm in another area. If the system uses storage at one or more of the stations, the storage is almost immediately exhausted, creating the double problem of managing the rest of the system while releasing storage in the exhausted area.

Pump Stations with Small Storage Capacity -- Certain CATAD control system pumping stations also have small storage volumes available. Among these are the East Marginal Pump Station in the southern area and the 30th Avenue and Belvoir Pump stations in the north. Storage volumes available at these stations are so small that it is impractical for an operator to attempt to use this capacity in the supervisory mode since the wet wells could easily rise to a flooding condition before the operator could respond to the condition. In any case, the storage volume gained would be insignificant in a total storage strategy. This limitation is equally true in automatic control mode.

Overflow Weirs Causing Reduced Storage -- Most regulator stations are protected against a critically high trunk level by an overflow weir. Weirs are constructed to act as a fail safe device so that overflows will occur when the trunk reaches a designated maximum level, even if the outfall gate does not function. This protection mechanism may not work in a high tide condition. Emergency weir overflow lines are normally protected by a flap gate which will not allow high tide level waters to flow back into the sewer system. The overflow weirs are usually not a factor in the CATAD control system operation. There are, however, infrequent occasions where an emergency weir location lower than the actual maximum trunk level prevents use of a small increment of storage in a trunk. This lost storage is usually very small, but in some cases, could be quite valuable.

Two important overflow weirs occur in the system separate from regulator stations. One of these is in the Elliott Bay Interceptor upstream of the Interbay pumping station; the other is at the Fremont Siphon under the Lake Washington Ship Canal.

The purpose of the Elliott Bay Interceptor weir is to limit the total flow reaching Interbay and protect the station from dangerously high flows which might cause flooding. This weir is positioned so that it does prevent the use of the total interceptor capacity for storage. It is undesirable to allow overflow directly from Elliott Bay Interceptor at this location since primary settled sludge from the Renton Treatment Plant as well as separated sanitary sewage flows are directed to the West Point Plant through this interceptor. An overflow would consequently have a more serious effect on water quality than a stormwater diluted overflow directly from a trunk line. Control system operation may use interceptor capacity only up to the level of this weir.

The Fremont Siphon weir limits the maximum flow through this structure. Overflow at the Fremont Siphon is directed into a fresh water body which is very undesirable. Storage upstream of the siphon must be manipulated to protect this location.

Stations Contributing Exceptionally Large Flows -- The Hanford Street trunk joins the Elliott Bay interceptor at the Hanford II Regulator Station. The Hanford Street trunk carries flow from a major area of south Seattle; the drainage area served by the Hanford Street trunk is much larger than other trunks meeting the Elliott Bay interceptor. This fact makes the Hanford II regulator a major factor in the operation of the Elliott Bay interceptor. Maximum interceptor flow is governed by the 120 mgd capacity of the Interbay Pumping Station. Under storm conditions, the Hanford Street trunk may carry over 50 mgd, so that this trunk line tends to have a disproportionate effect compared to the other twelve regulated trunks feeding the Elliott Bay interceptor. This imbalance causes control strategies for many regulators on the Elliott Bay Interceptor to be dictated by conditions within the Hanford Street trunk line. If the volume of this trunk were introduced into the system as more numerous, small connections, more variation in control strategies might be available.

Unsupervised Inflows -- Larger trunks connecting to interceptors are controlled by regulators, but many smaller trunks are not. These unregulated connections make demands on interceptor capacity for which there is no real data gather facility. In periods of general rainfall, this is not a significant handicap since the contribution of the unregulated trunks can be estimated on the basis of known regulated flows. However, even though the flow in such an unregulated trunk may be estimated, it cannot be controlled. In periods of unevenly distributed rainfall, estimation of such flows is difficult.

Uncontrolled and unmonitored inflows to the interceptor system hinder precise control system operation. If all inflows were monitored and controlled, the CATAD system could effectively predict and dictate flow conditions throughout the interceptor system. As the percentage of monitoring and control stations decreases, concessions must be made to approximation, which is often barely adequate. For operation of a CATAD-like system, the number of unmonitored and uncontrolled inflows to the system must be minimized.

Critical Elevations -- Operating experience with the CATAD system supervisory control mode has indicated three locations where storage use is impeded by low connections to trunk sewers. At the Eighth Avenue South, Chelan Street and Brandon Street regulators, sewage backup of low areas in nearby residences and businesses connected to the corresponding trunk sewers occurred during some storms while trunk levels were below their designed maximum. Evidence indicates that existing connections at levels below the trunk line design are not protected by one-way valves. Consequently, maximum storage levels at these stations must be reduced below the original design. These limitations are not now critical since the storage volumes in these trunks are not heavily used for most storm conditions. It is possible that these connections will have to be corrected to handle expanded requirements in the future.

OPERATING EQUIPMENT PROBLEMS

The CATAD control system depends on reliable, accurate operation of sewage handling equipment in regulator and pumping stations and treatment plants to implement its control strategy. Scheduled and emergency loss of operating equipment affected the CATAD system efficiency during early operation.

Regulator Stations Out of Service - For several months during early CATAD system operation, three major Elliott Bay regulator stations were unavailable, partially or completely, for CATAD use due to station modification. The Brandon and Michigan Street regulators were completely out of service while being modified. The Hanford Street II outfall gate was removed from service for an extended period.

Removal of the Brandon and Michigan Street regulators from service prevented control of a large portion of upstream storage on the Elliott Bay Interceptor, dictating more drastic control measures at downstream stations. Greater overflow volumes occurred due to loss of upstream storage volume.

Loss of outfall gate control at Hanford Street II was not a serious control problem. Station modification plans called for loss of regulator gate control as well as outfall gate control. However, the Hanford Street I station on the Hanford Street trunk provides a gate for diverting sewage into a storm sewer which serves as an overflow structure. Relative trunk level elevations at the two stations allow storage held behind the regulator gate at the Hanford Street II station to be relieved by overflowing at the Hanford Street I station. Thus, the storage capacity of the trunk line could be used without causing excessively high levels as long as the Hanford I regulator was available for control. This scheme was used satisfactorily while the Hanford Street II outfall was out of service.

Gate Sensors - Regulator and outfall gate positions are sensed with multiple turn wire-wound potentiometers mechanically linked to the gate operating mechanism. Potentiometers and mechanical linkages have failed completely or developed intolerable amounts of variability as usage increases. Failures of this type cause loss of automatic control of a regulator or outfall gate for a few hours or days until maintenance can correct the situation. In critical periods of intense rainfall, maintenance personnel are usually on call to correct such situations, so that downtime exceeding a few hours in critical situations is uncommon. Even a few hours, however, can cause a large increase in overflow volume.

Pump Problems - All flow from the Elliott Bay Interceptor must be pumped through the Interbay Pumping Station. Three engine driven pumps are available at the Interbay station with a maximum of two pumps operating simultaneously to provide the station's design flow of 120 mgd. During the first year of CATAD operation, numerous problems were encountered with the engines driving the pumps at this station. The engines are fueled by either natural gas or propane. At various times speed governor malfunctions, carburetion difficulties and other engine problems caused pumps to go off line, drastically reducing station capacity. When an engine drops off line, an operator at the station must either manually restart that engine or start the third engine to replace the one which failed. Since the station is manned only on a regular 7:00 a.m. to 4:00 p.m. Monday through Friday shift, engine failure during high flow conditions can be disastrous.

For much of the wet winter season of 1972-73, engine problems plagued the Interbay station. For many months only two pumps were available since maintenance of the third pump was delayed waiting for scarce replacement parts. It was not always possible to run both pumps at their designed maximum capacity due to problems with an overspeed limiter on one of these pumps. Several times, while the station was running at maximum available capacity, a pump dropped off line. When pumping capacity is suddenly halved, the station wet well level immediately jumps to a flooding condition initiating total station shutdown by automatically closing an influent control gate. When this occurred, the CATAD console operator immediately called out maintenance personnel to attempt to restart the station. In the interim, available storage capacity was used in an attempt to prevent overflows until the pumps at Interbay station were restarted. This strategy was often ineffective since a major portion of the total system's storage was already filled by high storm flow conditions. Large overflows often resulted. The critical location of this station makes improved maintenance and operations procedures mandatory to keep the station at full strength in fucure winter periods if the CATAD system is to perform in an optimal manner.

Lake City Tunnel Surge - The major storage volume for the north section of the CATAD control area occurs in the Lake City Tunnel controlled by the Lake City Tunnel Regulator. This facility provides an exceptionally large volume of storage: up to 6.5 million gallons. During December, 1972, the Green Lake Trunk, which crosses the Lake City Tunnel, was diverted into the Tunnel to allow maintenance to be performed downstream on the Green Lake Trunk. The increased tunnel flow decreased total storage time available in this facility. During high intensity storms in December, 1972, and January, 1973, tunnel storage was used up to the maximum safe value indicated by available system data. Twice, serious surge conditions occurred in the Lake City Tunnel sending large volumes of sewage traveling up the tunnel and out through the influent structure at the upstream end of the tunnel. The violent expulsion of a large quantity of sewage from the tunnel damaged the influent structure and washed out a gravel roadway leading to the station. To prevent further damage, including possible tunnel damage due to excessive internal pressures, storage in the tunnel was suspended until an investigation of the situation could provide an hydraulic explanation of the facility's behavior. Preliminary analysis indicated the surging condition was initiated by movements of the regulator gate at the downstream end of the tunnel while high head conditions existed due to the large volume of storage. Diversion of Green Lake trunk flow into the Lake City Tunnel may have been a contributing factor. The diversion was terminated in March, 1973, and storage has been allowed to levels considerably below the original maximums since that time. Final operating guidelines will not be implemented until a full study of the surge conditions is completed. Until then, a serious restriction in control strategy exists because of the limited tunnel storage volume.

West Point Treatment Plant Operation Problems - Two conditions at the West Point Treatment Plant required lower than normal limit on plant flow and, in storm conditions, caused earlier overflows because of more rapid usage of storage.

First was the loss of some primary sedimentation tank facilities due to machinery malfunction. Some situations make it necessary to completely drain a tank to make repairs. This decreases the total flow rate which the control system can send to the treatment plant with obvious adverse effects.

The second problem at the West Point Treatment Plant is overheating in effluent pumping engines. The plant must have pumps to discharge its effluent to Puget Sound under high tide conditions. At low tide, gravity flow handles the discharge. The problem of high tides coincident with high storm flows was discussed earlier in this section. This problem is further complicated when the engines driving the effluent pumps at the treatment plant have been subject to overheating problems through periods of prolonged use. When a portion of the effluent pumping facilities must be shut down under excessively high tide conditions, the control system is faced with the dilemma of high storm flows, low treatment plant capacity and no overflow capability.

Communications

CATAD control system operation has inserted a new group of people into the standard operating procedures of the Metro sewer system. Prior to CATAD all operating aspects of regulator and pumping stations and other facilities were handled by personnel based at the main treatment plant where the collection facilities terminated. Operations and maintenance personnel were centered at the West Point and Renton Treatment Plants to support facilities related to each plant. The CATAD control system involves the facilities of both areas. No specific plan was made to introduce CATAD system operation into the standard operating procedures of the Metro sewer system. Metro has been largely dependent on a consultant for engineering services pertinent to the physical sewerage facilities. No specific plan was made to provide lines of communication with these consultants for the CATAD facility. Inadequate planning in these areas has introduced some difficulties in CATAD control system operation.

Controlled Facilities Engineering Data - To operate any controlled facilities in either a supervisory or automatic mode, it is necessary to have an operational profile of the facility. This information includes pipe inverts and sizes, gate inverts and sizes, pump characteristics, etc. It was discovered soon after the initial control system installation that such data was often missing, inaccurate, or difficult to locate. The problem became critical when the first phases of supervisory control were initiated. At that time operators often found that there was not enough data available to indicate limits of storage, flow rates, etc., that could safely be attempted at a given facility. Time has alleviated this difficulty as more information is found. However, new controlled facilities being added to the system present many of the same problems as the initial implementation. Difficulty obtaining accurate physical data about stations indicates a deeper problem of recording "as built" data on installed facilities. Lack of this data hinders operation of the control system. In some cases stations were not used even though they were physically ready for control because the necessary operational data was not available.

Operator Records - To evaluate CATAD system operation and provide improved operating procedures, it is necessary to have a history of operation. The record-keeping procedure was especially important for early development of supervisory control procedures. The need for good record-keeping procedures at the operator's console was not foreseen, and procedures have developed slowly. As the automatic control mode takes over system operation, such records become less important, minimizing future problems due to lack of such data. As the automatic control system replaces the supervisory control procedure, the need for more than one console operator diminishes. During the supervisory control period, two operators attempted to cover all control requirements for the system. The operators replaced each other on a rotating shift basis during storm periods, making it necessary to pass operational information from person to person to maintain the continuity of a control strategy. No specific procedures were designed to implement this information transfer; consequently, operating errors occurred. The overall impact of these errors was small in terms of overflow volume. For a system permanently operated in a supervisory mode, detailed communication procedures must be established and checked to enhance operator efficiency.

Interface Between CATAD and Operations Personnel -- The CATAD console operator now has the most detailed knowledge of Metro sewer system operation excluding the treatment plants. The CATAD console operator observes the operation of each facility within the CATAD system and calls out operations and maintenance personnel to check and/or correct any problems he finds. Some communication difficulty has occurred between the CATAD operator and operations and maintenance personnel due to the essentially different "vocabulary" familiar to each. Regular maintenance and operations personnel deal with the physical gear at the regulator and pumping stations. The CATAD operator deals with data telemetered from the remote station and attempts to interpret the operating condition of station equipment from the displayed data. The communication problem arises from the fact that a malfunction detected by the control system and alarmed on the basis of apparent symptoms often has a cause in a completely different area. The console operator uses a selected set of computer data to make decisions. It is difficult to give personnel involved with mechanical, hydraulic, electrical and other physical gear a good explanation of a problem to aid in their maintenance effort. Field crews generally know little about the operation of the computer control system. They may not understand the vocabulary which the console operator uses to describe a problem or comprehend the procedures involved in getting data from the station to the CATAD system. It would be valuable to cross-train console operators in basic maintenance skills, especially instrument operation, and give maintenance personnel a basic understanding of the control computer's operation.

Supervisory Control Console

A basic plan for the operation of the CATAD system from the operator's supervisory control console was laid out in the original system specification. Console operating experience has led to many minor operating procedure revisions. Some significant console problems deserve mention in a discussion of system operating difficulties.

Events Printer -- Console room hardware design provided enclosures for the events and logging teletypes to reduce the noise level from these devices. However, the noise covers became quite impractical. The cover design significantly lowered the noise level but also made it difficult to see the printing on the teletypes. One purpose of the events printer is to log a verification message for each operator command before it is entered. Using this facility, the operator should visually verify each command on the events printer before entry. The noise enclosure makes the operator move away from his normal operating position to read the messages on the events printer. This has led to an operating procedure where the operator does not verify his commands, resulting in occasional errors of operation, especially during the busiest storm periods.

Lack of Operating Data -- Original design of the operator's console called for a single station data display format on the CRTs. This single format provided a display of the basic analog values being scanned for each station in the CATAD system. However, one significant piece of data, the accumulated rainfall, was not available except by special request for a printed log. Rainfall data is quite important to an operator performing supervisory control of a portion of the system since it indicates future runoff locations and quanitities with which the operator must deal. This problem was solved by providing a group of display formats, each individually selectable by the console operator, which allow a greater spectrum of data to be displayed. This development has made data available on the CRT displays which originally was available only on one of the teletype printers. The operator's task has been centralized at the control console with less dependence on the peripheral printers.

Command Completion Difficulties -- A major hindrance to early supervisory operation of the sewer system was the lack of accurate data on the operating characteristics of station equipment. The most common problem was inaccurate information on the rate of regulator and outfall gate motion. With inaccurate data, it was difficult to get correct results from gate movement commands since the expected gate performance did not agree with the actual situation. As these problems were eliminated by collecting more up-to-date data, further difficulties in the hardware telemetry system affected the system's ability to successfully complete an operator's commands. These difficulties and their solutions are discussed elsewhere in this report. From the console operator's standpoint, the net effect of all the commanding difficulties was the necessity to reenter commands, often three or four times, to achieve the desired results. This slowed implementation of the desired control strategy and made the operator's hectic job even busier.

Pump Station Setpoint Restrictions -- After a period of supervisory operation of the system, the consulting engineer realized that the commanding procedure allowed the console operator to request pump operation which might result in pump cavitation. It was decided to prevent the operator from requesting pump operation that might be detrimental to the mechanical integrity of the sewer system. Originally, this limitation would not allow the operator to request a higher pump speed than would have been used by the station functioning in the local control mode. This would severely limit control system performance since higher than normal pump speeds are often used at the beginning of a storm period to pump as much sewage as possible out of an interceptor to create the greatest storage. The approach finally adopted consisted of checking a requested pump setpoint against safe limits established by a study of the operating properties of the individual pumps. This solution allows the greatest control of pump operation while protecting against serious damage.

Flow Commanding -- In addition to the basic command procedure of requesting gate positions and pump setpoints from the operator's console, an additional function allows commands entered as requested flows. This procedure allows the operator to request the flow quantity in mgd which he wishes to have diverted through a regulator gate or pumped by a pumping station. Programming provided by this capability checks the gate position or pump setpoint periodically and issues commands necessary to maintain the desired flow rate. The flow commanding facility eases the operator's chore by making it unnecessary for him to continually monitor water level changes at all the stations and adjust for variations. Programming problems were encountered during the development and early implementation stages of the flow commanding algorithms. These problems involved erroneous operation or complete failure of flow commanding. The supervisory operator was often required to fall back on the more basic command procedures. Flow commanding problems were eventually eliminated and this facility is now integral to both supervisory and automatic control schemes.

Satellite Console

Through the initial CATAD development period, the satellite console at the West Point Treatment Plant has been the control and observation point for the system when the central console facility is unmanned. A special section describes the operation of this satellite terminal. Reliance on this terminal has caused some difficulties for the CATAD operator in maintaining the supervisory control scheme.

Operator Training -- West Point Treatment Plant personnel who monitor the satellite console have training concentrated in treatment plant operation. No effective special training sessions have been provided to instruct the console operators in the operation of the remote terminal or to provide them with background concerning the facilities the CATAD system monitors. Treatment plant operators have been forced to learn about CATAD system operation by using the system. This is not the best approach since these individuals perform the major portion of CATAD system monitoring. Knowledgeable operation of the CATAD system requires understanding functions of the various regulator and pumping stations, background in the physical constants pertinent to each station's operation, and knowledge of the operational methods of CATAD monitoring and control facilities. Few, if any, of the West Point operators have sufficient training or experience to develop this level of understanding. Sickness and personnel turnover also contribute to the variability of operator experience. The satellite terminal operators lack of background makes the CATAD console operator's job vastly more difficult. One of the CATAD console operators is available on a 24-hour on-call basis to handle problems related to the CATAD facility. The operator on call depends on the personnel monitoring the remote console to observe and recognize significant alarm conditions and notify him of the need for action. Many times, important conditions which should have resulted in immediate operator notification have gone unresolved for a number of hours. Even more frequently, the CATAD operator receives unnecessary calls at all hours because the treatment plant operators cannot discriminate significant conditions from unimportant ones. Consequently, the CATAD operator has a much heavier responsibility. He must be able to interrogate the West Point operator and aid him in the operation of the remote facility to get the information necessary to make a knowledgeable judgment about required action. This commentary is not condemnation of the treatment plant operators. Rather, it points to the need for support personnel to provide adequate initial and regular refresher training to all console operators.

Limited Operations from the Remote Consoles -- Even with adequate manning of the remote consoles, problems would still exist. The remote consoles provide a monitoring facility, but not a control station. The monitoring capability is limited also, since data available at the central console is not available to the remote consoles. A major omission from the remote console displays is rainfall data, which is nearly essential for making intelligent evaluations of system operation.

The remote consoles cannot truly be called control consoles since they only allow one command; removing a station from supervisory or automatic control and returning it to the local control condition. The lack of command facilities again makes the CATAD console operator's job more difficult. Whenever the operator is notified by the treatment plant personnel of a problem that occurred outside of the normal shift of the console operator, the operator must return to the central console control facility to perform remedial action. He cannot request that the remote console operator perform the required functions from his terminal.

All monitoring and control functions of the satellite consoles will eventually be implemented with additional software. At that time the satellite consoles will duplicate, at a slower speed, all central console functions. Improved system reliability and ease of use should result.

Console Operators

The success of the CATAD system depends on the console operator in two ways. First, the operator must be sure that all necessary functions to achieve a storage strategy are operating correctly at all times. Secondly, whenever supervisory control operations are to be performed, a console operator must run the system. Introducing the automatic control scheme lessens the amount of operator time required on 24-hour call basis to handle emergency conditions. A number of factors have limited the console operators during the period of CATAD operation to date.

Training Time -- The console operator requires knowledge of many phases of the operation of the sewer network, control stations and the computer facility. A training period of approximately one month should introduce an operator to the basic layout and functions of the control console and the standard procedures used by console operators. However, experience with operators working at the console indicates that even after six or more months, they may still be learning about standard console operation and especially about the remote facilities. This long learning time is simply explained by the huge volume of information to assimilate. For an operator to be effective at supervisory control of the sewer system, he must not only know the maximum limits of storage and other related parameters appropriate to each station, but he must also have an intimate awareness of available storage volumes, gate movement times, runoff delays from initial rainfall, sewer flows as a function of rainfall volumes, and many other characteristics which are not easily represented as numerical data. Much knowledge has been developed by the CATAD operators about the "character" of each station in the control system. It is development of this in-depth understanding of an overall system which allows effective use of the control system in a supervisory mode. The basic operator learning curve could be significantly shortened if a truly thorough operator's manual were available including a full description of console operating procedures; all physical data pertinent to station operation; text instructions and comments about the operation by experienced operators; sections to allow operators to enter additional pertinent data, comments, observations, etc., concerning the operator's console, remote station equipment, station operating characteristics, etc., as new information became available. Such a manual (see Volume III, this report) takes a long time to develop and more important, must be regularly and rigorously updated to reflect the most current system procedures.

Maximum Human Optimization Capability -- The console operator's job when running the system in the supervisory control mode is to optimize the use of storage volumes to minimize raw sewage overflows. For short duration storms of limited geographical coverage, it is possible for the operator to consistently eliminate all overflows. However, as the total geographical, chronological and volumetric impact of a storm increases, the difficulty of the operator's job increases exponentially. The degree of difficulty of the operator's job is a function of the total sewer system operation which must be monitored, understood and controlled by active involvement in a real-time mode. To be able to approach an optimal use of storage resources, the operator must visualize the rainfall pattern over the area and allocate storage appropriately.

As the rainfall pattern changes, the operator must dynamically alter his storage and control strategy. Rainfall alone, of course, is not sufficient data on which to base a control strategy. The most important data item for control is trunk sewer flow. However, if the operator waits for the storm flow to reach regulator stations to get an accurate measurement of the flow, his control actions will most likely start too late. The operator must anticipate flows and the time of their major impact through the system to implement an effective control strategy. In the CATAD system an operator may be expected to implement a control strategy involving fifteen or more stations, continuously monitor these stations and modify their gate positions or pumping rates to make best use of the available storage resources. Experience indicates that fifteen stations under supervisory control is the maximum which even the best qualified operator can handle. A work shift of eight to twelve hours of such activity is extremely demanding.

Reaction Time to Off Duty Callout -- Storm conditions may begin when the central control console is not manned. When this happens, the on-call CATAD operator is notified by the West Point operator who is monitoring the satellite terminal. If the supervisory control mode is to be used for storm control, the operator must have enough notice to allow him to reach the control console and initiate an effective strategy before the major flow conditions are upon him. During early operation of the system, the problem of getting adequate notice to the operator caused some possibly unnecessary overflows to occur. Experience with the CATAD system has generally alleviated this problem.

Working Conditions -- CATAD console operators are subject to periods of very high activity alternated with periods of low activity. The most intense requirements occur during the wet winter season; however, during the development period of the system, the operators have also been required to respond to off hours system failures detected by monitoring at the West Point terminal. From early 1972 when the supervisory control program began, Metro has operated the control system with two men available as console operators. One of these men is a console operator; the other a programmer who acts as console operator when required by storm conditions or other circumstances. During the wet winter months of 1972-73, it was not uncommon for each operator to work over 40 hours of overtime in a month with maximums of over 70 overtime hours a month. If supervisory control is to be a normal operating mode, it would be wise to employ at least four operators to work a scheduled rotating shift. Where automatic control is replacing the intermediate step of supervisory control, the two operators have been able to handle the interim period although at times the demands on these employees have been far beyond reasonable expectations. In addition to long working hours, the console operators are subject to considerable mental pressure since it is their responsibility to minimize overflow volumes. A few times during the 1972-73 winter, the condition occurred where high tides and high storm flows combined to force excessively high trunk levels. In these cases, an operator must do all in his power to avoid flooding residential and commercial sewer connections. The overall operation of the CATAD system during the rainy winter period puts considerable pressure on the individual operator.

Intra-Agency Cooperation -- It is the responsibility of the CATAD console operator to observe the operation of the sewer system and its control components and notify the required maintenance personnel when problems are detected. Maintenance personnel are not always available and when a scheduling conflict occurs, the maintenance director decides which functions have priority. The CATAD control system is a recent addition to the Metro sewerage operation, and many more "veteran" aspects of the operation are accustomed to being higher on the list of maintenance priorities. The fact that the CATAD system has been installed and is operating in an area separate from the standard plant and system operations has hindered easy integration of the CATAD effort into the total Metro sewerage operation. In areas where it is necessary to receive the cooperation of other operating and maintenance personnel, the fact that CATAD has been an isolated and often misunderstood effort has certainly caused some difficulties. Any agency attempting to introduce a CATAD-type system would be well advised to educate everyone who would have to have contact with the system to minimize misunderstandings arising from ignorance. Kudos as well as the criticisms should be evenly distributed among those playing a part in the total system to achieve a maximum acceptance and efficiency.

SECTION IX

WATER QUALITY STUDIES

INTRODUCTION

The Seattle Metro comprehensive water quality monitoring program started in 1963. Additional stations and parameters were added in 1967 to assess the impact of combined and separated sewer overflows within the Metro drainage basin (Figure 69). The CATAD demonstration project to improve receiving water quality by reducing overflow frequency and volume included detailed analysis of physical, chemical and biological data from both combined and separated sewer overflows. This data must be correlated with the corresponding meteorological parameters: temperature, rainfall intensity, duration and frequency.

The two major water quality data collection objectives for this report were:

1. To show the dynamic water quality effects of Metro's sewage interception, regulation and separation program.
2. To establish a water quality parameters baseline relative to CATAD demonstration project implementation.

Data analyses and conclusions are presented in Section X. This section considers water quality data which indirectly relates to the sewage collection system and to the immediate and overall receiving water quality. Related water quality studies, completed or currently underway, which might bear significantly on combined sewer overflows are discussed.

COLLECTION SYSTEM STUDIES

General

For this demonstration grant, regulator station studies focused on combined sewer overflows, primarily in Elliott Bay and on the Green-Duwamish River. Because of the potential impact of the large sewer separation program described in the interim report (12), special consideration is given to the water quality changes at those regulators serving areas which have undergone separation (Appendix A). The water quality impact of large paved areas such as freeway drainage, as developed in several recent studies within King County, is included to relate stormwater runoff to the combined sewer overflow loading.

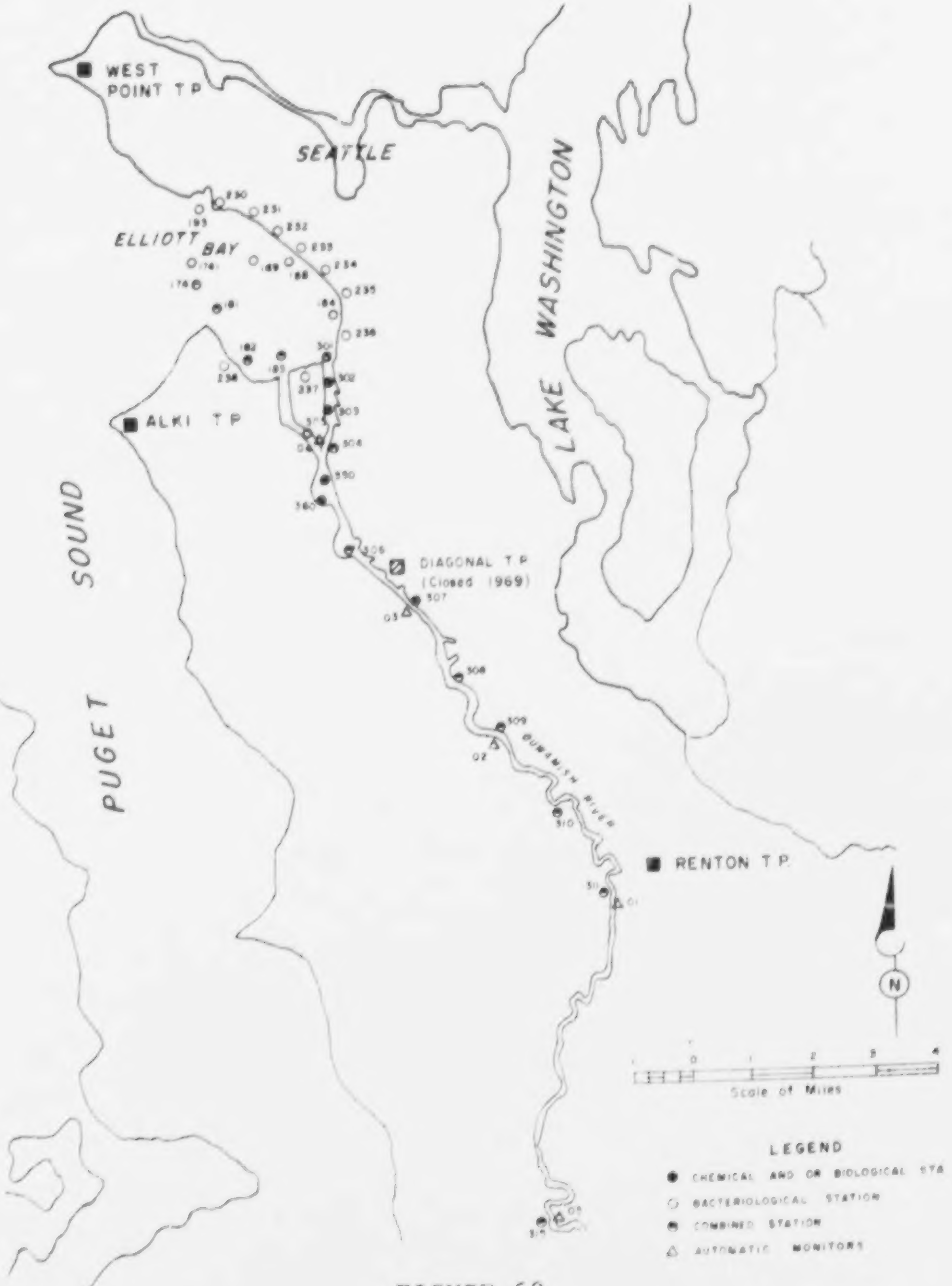

WEST POINT T.P.
SEATTLE
LAKE WASHINGTON
ELLIOTT BAY
ALKI T.P.
SOUND
PUGET
DIAGONAL T.P.
(Closed 1969)
DUWAMISH RIVER
RENTON T.P.
230
193
231
232
233
234
235
184
236
176
181
182
183
238
237
301
302
303
304
350
360
305
307
03
308
309
02
310
311
01
N
0
1
2
3
4
Scale of Miles
LEGEND
● CHEMICAL AND OR BIOLOGICAL STA
○ BACTERIOLOGICAL STATION
◐ COMBINED STATION
△ AUTOMATIC MONITORS

FIGURE 69

WATER QUALITY MONITORING STATIONS
ASSOCIATED WITH THE CATAD DEMONSTRATION GRANT

Overflow Sampling Locations and Parameters

The overflow regulation objective was to minimize water quality degradation by reducing overflow frequency and volume. Overflow sampling was divided into physical parameters relating to the regulators, meteorological conditions, and water quality loading at each regulator site listed in Appendix A and illustrated in Figure 8.

The physical parameters include flow data; overflow volumes and frequency; rain intensity, duration, and frequency as well as average, maximum, and minimum daily temperatures.

The chemical data is based on chemical oxygen demand (COD), nitrite-nitrate nitrogen, ammonia nitrogen, total soluble phosphate, and solids analysis. Solids analysis includes total settleable solids, suspended solids and volatile solids.

The biological data includes biochemical oxygen demand (BOD) and bacteriological analysis. The membrane filter technique is used for total coliform, fecal coliform, and fecal streptococci. These tests follow "Standard Methods for the Examination of Water and Wastewater" (34) and have also been mentioned in the interim report (12).

Regulator Sampling

The CATAD sampling program began in November, 1969, with seven sampling sites. Six additional sites were added in April, 1971. At the end of June, 1973, the sampling program was reduced and data evaluation begun.

Sampling devices were either the Composite or Sequential Sewer-Test, Vary-Sampler, manufactured by Sirco Controls of Vancouver, British Columbia, Canada. Recording devices were two- or three-pen strip chart recorders manufactured by either Foxboro, Inc., Foxboro, Mass., or the Fischer & Porter Co., Worminster, Pennsylvania.

The major difference between the samplers is the method of sample collection. The composite sampler collects given amounts of sample at predetermined times after the initial gate opening and stores all samples in a single 12-liter glass bottle. Although individual samplers vary, approximately one liter is collected each time the pump is activated. Completely filling the bottle triggers a float switch, ending the sample sequence.

In the sequential sampler, samples are stored in separate one-liter bottles. Sample quantity is, therefore, fixed at one liter for each time division on the program tape.

Collected samples are stored in the sampler refrigeration unit as described in the interim report (12). Temperature in these units is maintained at 4°C to minimize biological activity or freezing which could alter the constituents of the sample.

Sample timing is accomplished by a rotating "Programmer disk" (see Figure 70) that opens and closes a microswitch supplying power to a vacuum pump. "Programming" the sampler consists of changing the position of ridges on an embossed adhesive tape. Sample sequences vary due to a size difference of the programmer disk furnished with newer model samplers. Sequences are listed in Table 19.

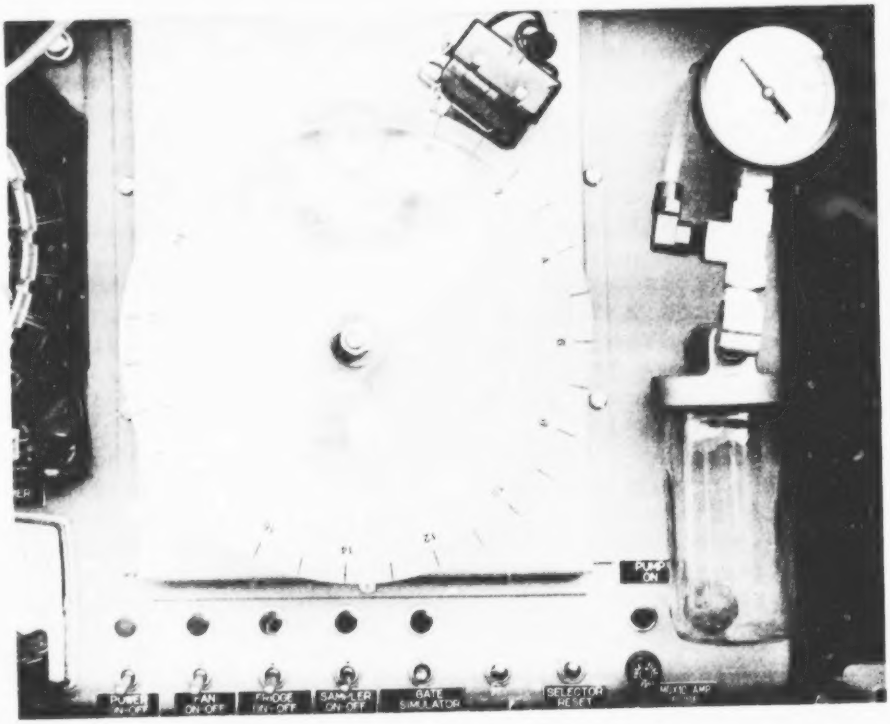

14
12
PUMP ON
POWER ON-OFF
FAN ON-OFF
FRIDGE ON-OFF
SAMPLER ON-OFF
GATE SIMULATOR
SELECTOR RESET
MDX10 AMP

FIGURE 70

PROGRAMMER DISK

Table 19. SEQUENTIAL SAMPLER TIMING

Stations	Time the Numbered Sample is Taken (minutes)								
	1	2	3	4	5	6	7	8	9
13 to 26	G.0.[a]	+15	+30	+45	+60	+90	+120	+180	@60
30 to 40	G.0.	+10	+20	+30	+40	+50	+60	+ 90	@60

[a] As outfall gate opens

Regulator stations utilize similar multi-pen color coded strip chart instruments to record: wastewater level in the sewer trunk, tide level at the outfall gate, and position of the outfall gate. Tide level is not recorded where it does not influence the overflow volume discharged. Representative loading figures for storm-related combined sewer overflows depend on successful operation of recorders, samplers, and on accurate laboratory analysis.

A technician is assigned to sample collection, sample analysis, some minor maintenance and inspection, and coordination of supportive maintenance and data processing activities. Samples are collected after most heavy rainfalls. When time permits, the sampling equipment is left recharged and operational.

Routine inspection scheduling is determined by the reliability of the equipment at each station. Regulator samplers are checked once a week (more frequently if required). During maintenance visits, samplers are tested under conditions approximating an actual overflow condition. Problems are usually minor: sample tube blockages, microswitch adjustments, and fuse replacements. Recorders are marked and dated during inspection visits.

Recorder malfunctions and major sampler breakdowns are handled by an instrument technician from the West Point Treatment Plant maintenance section. Most tasks involve cleaning recorder pens and repairing faulty electrical components in the samplers. Maintenance crews performing other duties at the regulator stations periodically mark recorder charts and record outfall gate movements and sampler counter operations.

Metro's Water Quality Laboratory performs chemical analysis of the overflow samples. The laboratory is geared to handle large numbers of similar samples, so few difficulties were encountered during the study. High sample concentrations required a separate set of glassware to prevent contamination of other water quality samples.

Overflow samples are tested for eight different parameters using Standard Methods (34). Settleable solids are determined using an Imhoff cone, method #224F. Suspended and volatile solids are determined using Gooch crucible - glassfiber filter filtration, method #224C. Total suspended matter utilized method #224D. Biochemical oxygen demand (BOD) is determined by method #219, using a 5-day incubation period. Several dilutions are used to account for great variation in samples from different stations. Chemical oxygen demand (COD) is determined by method #220 using a 40-minute refluxing period and deleting the addition of Ag_2 and SO_4 to the concentrated H_2SO_4.

Until February 19, 1971, a hydrazine reduction method was used to determine nitrite-nitrate nitrogen (35). It was then determined that the cadmium reduction method (36) gave better results. This method was used for the remainder of the study, both in its manual form, and adapted to the Technicon Auto-Analyzer. A few drops of dilute $CuSO_4$ are added to sewage samples to remove any H_2S which would reduce the efficiency of the cadmium filings. Ammonia nitrogen is determined using the Nesslerization Method, #132B. Twenty-five milliliters of unfiltered samples are analyzed with a spectrophotometer rather than Nessler tubes. Phosphate is analyzed by the single reagent digestion method, #223B. Although listed as the Hydrolyzable Phosphate Test, this procedure gives values very close to the total phosphate concentrations. During the testing period, inter-laboratory standardization was initiated to check reproducibility of analytical results. This verified the quality of the laboratory results. Some difficulties were encountered in reproducing ammonia-nitrogen results with the Nessler procedure.

Flexible scheduling allows maximum use of available space, equipment and manpower. Metro's Water Quality laboratory is able to analyze large numbers of samples arriving at unpredictable times, with minimum conflict.

Data handling is usually confined to computing chemical and physical data, transferring overflow volume coordinates to worksheets, and logging pertinent data. Computer division personnel punch cards for both water quality parameters and overflow volumes.

Overflow volumes are determined from the chart records of trunk sewage level, tide level, and outfall gate opening. The computer program treats the gate as an orifice that may be submerged by tidal action (37). Overflow volume is the rate of flow multiplied by duration. The program accounts for scale factors between chart readings and water levels within the sewer (see appendix of Reference 12).

Sewer Separation Study

Seattle's $76,000,000 bond issue to partially separate all combined sewer systems tributary to Lake Washington included a cooperative study between Metro and the City of Seattle to determine the quality and quantity of overflows with separation, as well as the impact of CATAD computerized storage management. Of the four stations sampled (see Figure 71) Cooper Street represents a small (103 acres) and Sand Point a larger (183 acres) drainage area served by a separated system. Windemere and Henderson represent large combined systems from 448 and 539 acres, respectively. Equipment and primary analysis are discussed in the interim report (12). Most data collection utilized a vacuum type, clock-motor drive sequential sampler and a seven day chart, clock-driven flow level recorder.

The quality and quantity of the separated stormwater and combined overflow streams were measured over a two-year period at sample sites in four different drainage basins. Quality measurements included total and fecal coliforms and fecal streptococci, total phosphate, ammonia and nitrite-nitrate nitrogen, settleable, suspended and volatile solids, BOD and COD. All analyses were conducted in accordance with Standard Methods with the exception of ammonia (38). Quantity data was computed from stage height recording. Rainfall data discussed in Section X was obtained from the City of Seattle's rain gage network described in Section IV (see Figure 11).

Freeway Drainage Study

The objectives of this study for the Washington State Highway Commission were to define the quality of the stormwater runoff from highway surfaces and to estimate the environmental impact of such runoff (39).

Two freeway drainage studies were conducted. The first, on an elevated portion of Highway I-5 (see Figure 72) during 1970-71, was chosen because of the lack of interference from other sources of drainage. The second study on the I-90 corridor from North Bend to Lake Washington (see Figure 72) examined the impact of additional traffic and road surfaces in the area.

Parameters measured in the I-5 study consisted of antecedent rain, suspended and settleable solids, COD, BOD, nitrite-nitrate nitrogen, total phosphate, free ammonia, and oils which were measured by the Soxhlet extraction process (40). Most of this data was presented in the interim report (12). During the I-90 study, traffic volume and its impact on amounts and types of residual material deposited were added. Airborne dust from background sources not attributable to vehicle emmissions was also measured.

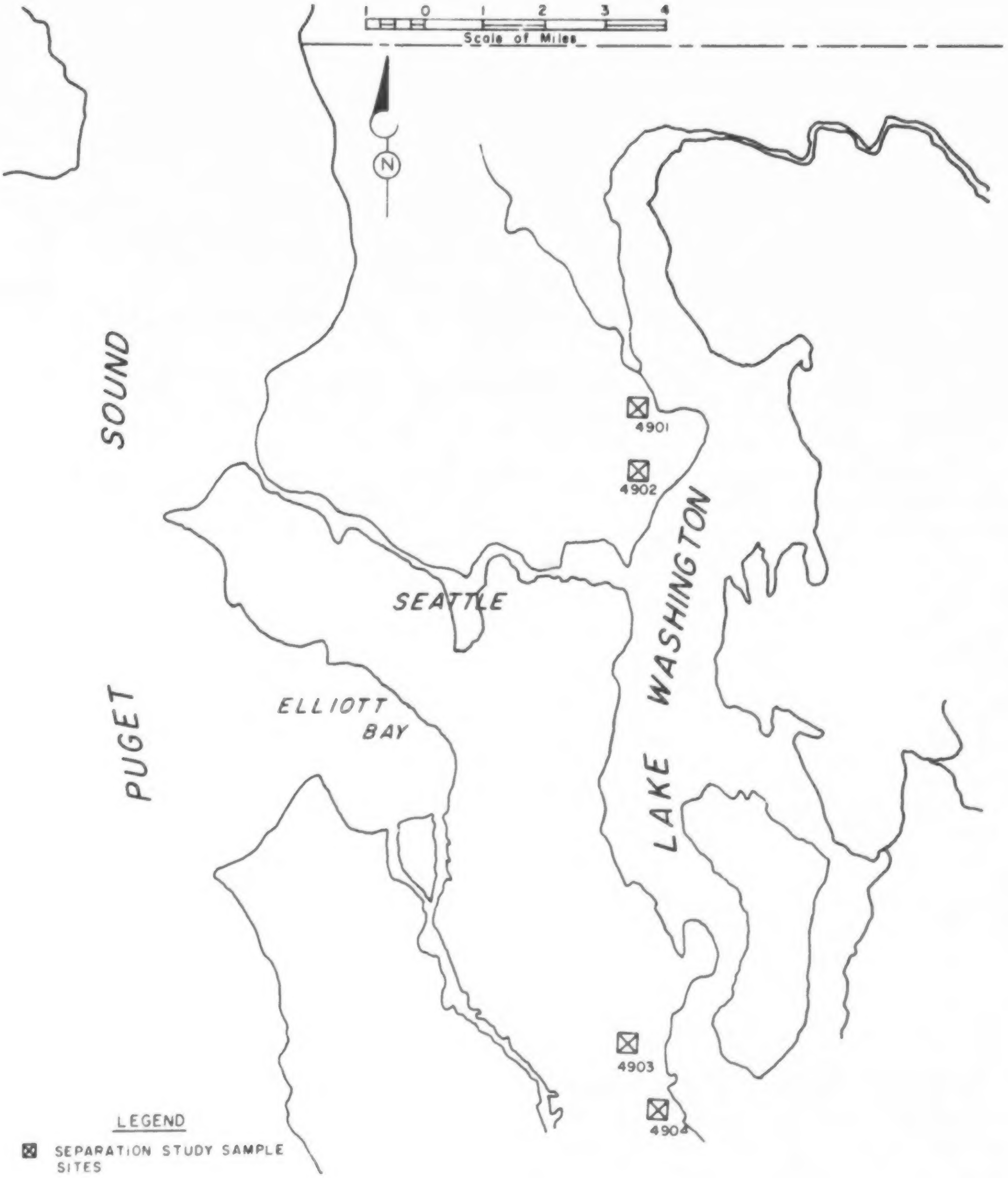

1 0 1 2 3 4
Scale of Miles
N
PUGET SOUND
SEATTLE
ELLIOTT BAY
LAKE WASHINGTON
4901
4902
4903
4904
LEGEND
☒ SEPARATION STUDY SAMPLE SITES

FIGURE 71

STORM SEWER SEPARATION SITES

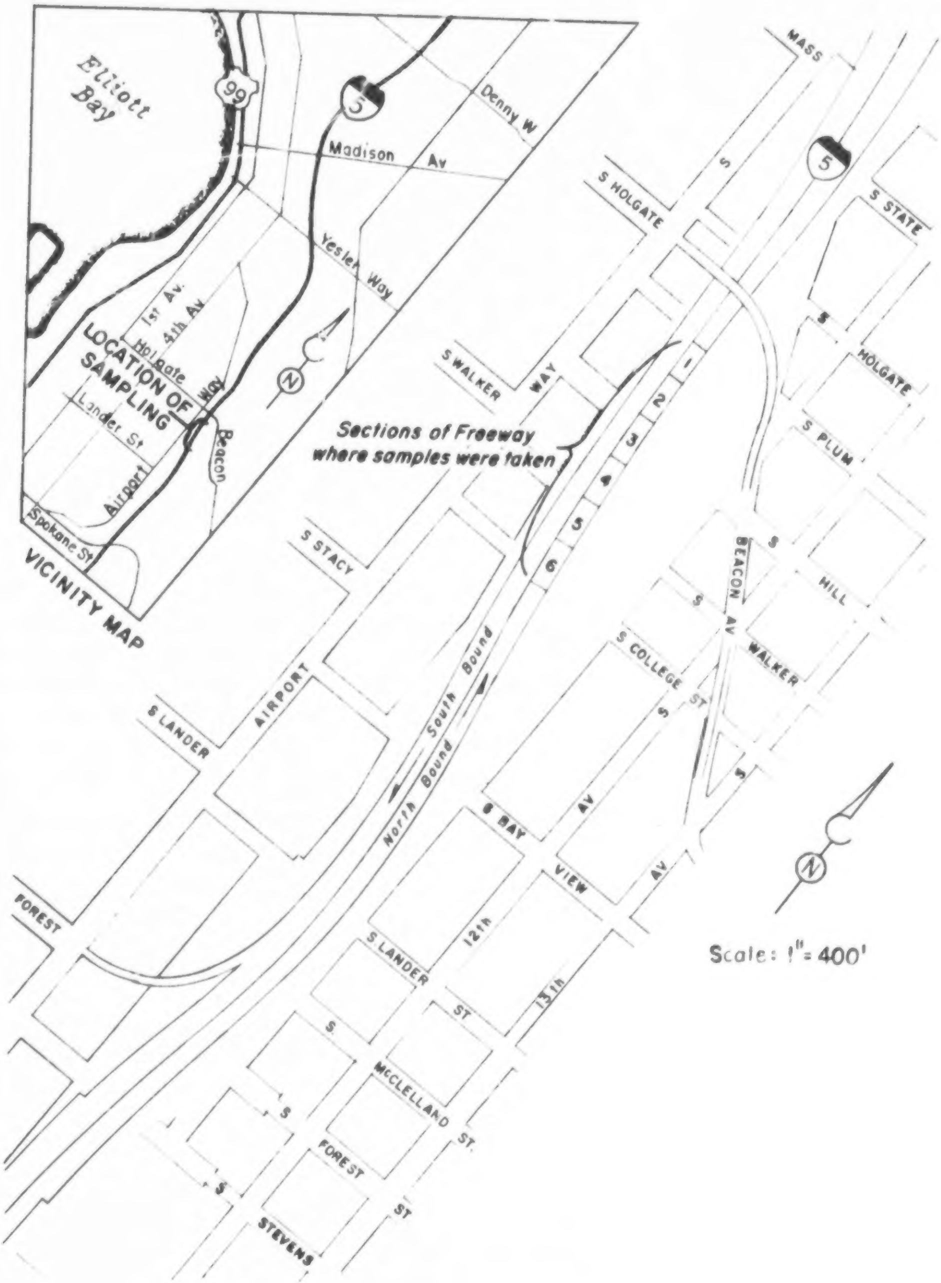

Elliott Bay
99
5
Denny W
Madison Av
Yesler Way
1st Av.
4th Av
Holgate
LOCATION OF SAMPLING
Way
Beacon
Lander St
Airport
Spokane St
VICINITY MAP
N
MASS
S
5
S HOLGATE
S STATE
S WALKER
WAY
S HOLGATE
S PLUM
Sections of Freeway where samples were taken
1
2
3
4
5
6
S STACY
S HILL
BEACON AV
S WALKER
S COLLEGE ST
S
South Bound
North Bound
AIRPORT
S LANDER
S BAY VIEW AV
12th
13th
S LANDER ST
S MCCLELLAND ST
S FOREST ST
S STEVENS
FOREST
N
Scale: 1" = 400'

FIGURE 72

FREEWAY DRAINAGE STUDIES

The I-90 study was divided into three phases. The first concentrated on the Mercer Island/South Bellevue area and Lake Washington. The second phase examined a typical highway construction site at Eastgate; and the third phase investigated the vicinity of North Bend, a semi-rural area crossed by a major highway.

Sampling crews were alerted to impending rainstorms through the cooperation of the National Weather Service-Federal Aviation Administration radar surveillance unit in Auburn, Washington. Runoff volumes from diverted drains were measured in 25-gallon containers at 15 minute intervals. Samples taken from more than one drain were composited every 15 minutes. 10 to 15 samples were collected for each storm of 4 to 6 hours duration.

Samples were separated into three portions: the original sample, the filtrate (from a 934 AH Reeve Angel glass filter), and the solids retained on the glass filter. Analyses were performed on the original sample for turbidity, conductivity, pH, settleable solids, total suspended solids, volatile solids, oil, COD, total coliforms and fecal coliforms. Analyses of the solids from the filtered samples included Kjeldahl nitrogen, total phosphorus, lead, zinc, copper, cadmium and chromium. Analyses of the filtrate were BOD, ammonia, nitrate-nitrite nitrogen, hydrolyzable phosphorus, lead, zinc, copper, cadmium and chromium.

The suspended solids analysis performed on the original sample included both the settleable solids and volatile solids. Oil content was determined by the Soxhlet extraction with a Freon solvent. An atomic absorption spectrophotometer was used for heavy metal analysis. Heavy metals separation was accomplished by particulate digestion with a nitric perchloric acid mixture.

Data Calculations

Significant data calculations included:

1. Mean Concentrations -- This value was determined for each constituent by summation of the total loading quantity calculated for each sample interval and dividing it by the total volume collected. The overall mean was calculated by averaging the means for individual storms.

2. Loading Figures -- The daily loading figure (mg/m^2/day) was calculated by totaling the individual loadings corrected for 100 percent runoff for each sample interval and dividing by the total area of the freeway drained and the number of days following the previous rainfall. The loading rate based upon traffic intensity was calculated

as a linear function of the drainage area (mg/m/vehicle). It was determined by dividing the total loading corrected for 100 percent runoff by the length of the area drained and the number of vehicles using the highway during the previous period.

The significance of the I-90 and I-5 studies to CATAD and runoff from the Metropolitan area lies in the fact that over 40 percent of the City's surface area is presently paved over for automotive related uses.

Urban Storm Drainage

Urban runoff data collection began in March, 1973, for six discrete basins of various land use; to determine pollution washoff characteristics in the Seattle area. To evaluate land use impact on overflow specifically in the CATAD control area, three of these basins were considered: the 800 acre multiple residential area View Ridge; 75 acres of commercial development with a high percentage of paved surfaces in South Center, Tukwila; and 100 acres of the Central Business District of Seattle (see Figure 73).

The View Ridge area has both single family and multiple family residential land uses. Most residential roof drainage downspouts empty into sanitary sewers. However, the results of monitoring this area, when compared to smaller areas, are quite valuable.

The South Center complex in Tukwila is open daily and evenings and experiences large volumes of automotive traffic. This area has a well-defined, separate, easily monitored storm drainage system. It represents a typical large commercial land use area.

Water quality parameters measured were: BOD, COD, dissolved oxygen (DO), ammonia nitrogen, nitrate-nitrite nitrogen, total nitrogen and phosphorus, suspended and settleable solids, dissolved solids, total and fecal coliform, chlorides, heavy metals (Hg, Cu, An, Pb, Cr, Cd, As, Fe), temperature, pH conductivity and turbidity.

Manual sampling consisted of sequential samples taken every 15 minutes as it began to rain. The alert system cooperating with the NWS-FAA radar surveillance and bellboy paging system developed during our freeway drainage studies were used in this study. Samples were collected using a bucket made from a Nalgene #2302 two-gallon aspirator bottle with the top removed at the shoulder. The spigot on the bottom of each bucket was fitted with rubber tubing and a pinch clamp. The bucket was lowered on a rope into the manhole, allowing sampling without entering the manhole. Where flows were

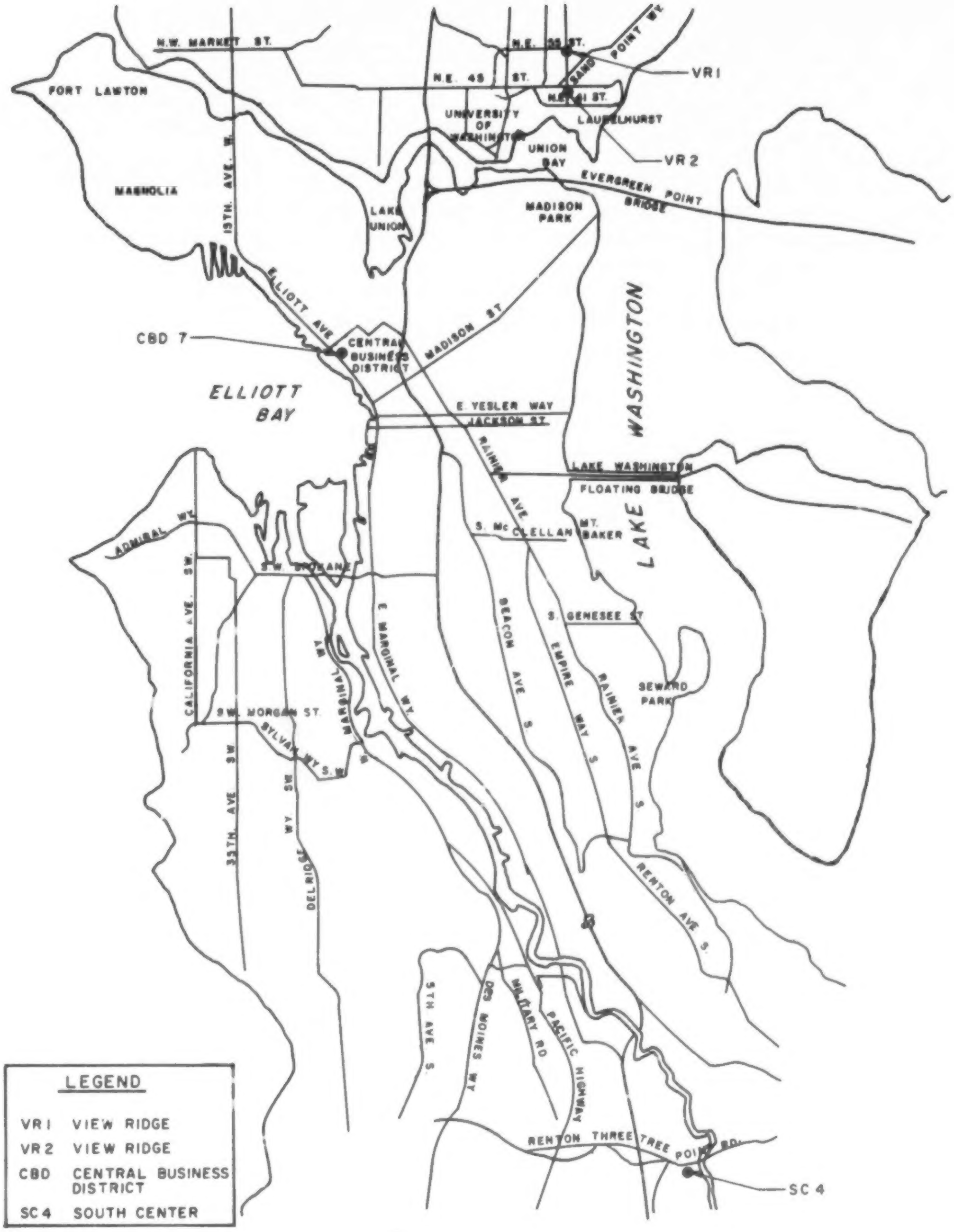

N.W. MARKET ST.
N.E. 55 ST.
SAND POINT WY.
VR1
N.E. 45 ST.
N.E. 41 ST.
FORT LAWTON
UNIVERSITY OF WASHINGTON
LAURELHURST
UNION BAY
VR 2
MAGNOLIA
15TH. AVE. W.
EVERGREEN POINT BRIDGE
LAKE UNION
MADISON PARK
ELLIOTT AVE
WASHINGTON
CBD 7
CENTRAL BUSINESS DISTRICT
MADISON ST
ELLIOTT BAY
E. YESLER WAY
JACKSON ST
RAINIER AVE
LAKE WASHINGTON
FLOATING BRIDGE
ADMIRAL WY.
S. Mc CLELLAN
MT. BAKER
LAKE
S.W. SPOKANE
CALIFORNIA AVE. SW.
E MARGINAL WY.
W MARGINAL
BEACON AVE S.
EMPIRE WAY S
RAINIER AVE S
S. GENESEE ST
SEWARD PARK
S.W. MORGAN ST.
SYLVAN WY S.W.
35TH. AVE SW
DELRIDGE WY. SW
RENTON AVE S.
5TH AVE S.
DES MOINES WY
MILITARY RD
PACIFIC HIGHWAY
RENTON THREE TREE POINT RD.
SC 4
LEGEND
VR1 VIEW RIDGE
VR2 VIEW RIDGE
CBD CENTRAL BUSINESS DISTRICT
SC4 SOUTH CENTER

FIGURE 73

URBAN STORM DRAINAGE AREAS

heavy and the bucket did not tip and fill upon hitting the water surface, an additional line attached to the spigot allowed the bucket to be tipped for filling.

One complete sample consisted of filling two one-gallon polyethylene jugs for general chemical tests (one sterile bacteriological bottle, one dissolved oxygen bottle), and recording the time and temperature. The spigot permitted aseptic filling of bacteriological sample bottles and collecting dissolved oxygen samples with minimal aeration. All samples were stored on ice while in the field. When possible, upon arrival at the sample site, a background sample was collected before the initial stormwater surge.

First flush samples were picked up one to three hours after the surge and returned to the laboratory where they were immediately preserved and analyzed. Additional samples were picked up at approximately three hour intervals. Since most storms lasted five to six hours, the second sample pickup was often delivered by the field crew when they returned to the laboratory.

Receiving Water Quality

The comprehensive receiving water quality program has been described by Gibbs (41) and Gibbs and Isaac (42), and results are available in Metro's six month reports to the Water Quality Monitoring Review Board. The two principal receiving water bodies relative to this demonstration grant are the Green-Duwamish River and Elliott Bay. Onshore and offshore manual and automatic monitoring stations are indicated in the map in Figure 69.

Manual Water Quality Monitoring

The Elliott Bay offshore stations are sampled twice monthly from the U. S. Geological Survey's 40 foot survey vessel RV Hydor and occasionally from a 16 foot outboard boat. Onshore sampling is made weekly. Samples are analyzed for total and fecal coliform, dissolved oxygen (DO), temperature, salinity, and transparency, using a secchi disk.

Nutrient data have been collected at four stations on a primary productivity study in Puget Sound from 1967 to the present. The productivity station 174 is very near Station 181 in Elliott Bay (see Figure 69).

In the Green-Duwamish River (the name changes from the Green River at the confluence of the Black River to form the Duwamish River below) demersal fish population data was collected between 1966 and 1971 using a 16-foot otter trawl boat. Total and fecal coliform, ammonia nitrogen, nitrite-nitrate nitrogen, and total hydrolyzable phosphate were manually sampled from the river. Studies on the benthic deposits of chemical oxygen demanding (COD) matter in the sediment were made for this demonstration grant with data available for the lower river between 1963 and 1973.

Automatic Water Quality Monitoring

Due to estuarine system complexities, Metro recognized that manual sampling to determine necessary water quality parameters at all stations under various tidal conditions in the Duwamish Estuary was impractical. Consequently, five automatic monitors were installed at strategic river locations. The multiple objectives of these monitoring stations were:

1. Demonstrate compliance with State water quality standards
2. Maintain a continuous surveillance of water quality conditions as they relate to the migration of anadromous fish such as salmonids
3. Document improvements in water quality conditions predicted as Metro's construction and operational program was initiated.

This monitoring program is being carried out in cooperation with the U. S. Geological Survey (USGS). The regional USGS branch is developing a complex water quality model of the Duwamish Estuary and relies on these automatic monitors for some of its primary calibration data.

Surface river water is pumped to the automatic monitor stations where DO, pH, conductivity and temperature are continuously recorded. In addition, river bottom water is monitored at the two downstream stations for conductivity, DO, and temperature. Data collected at the five locations shown in Figure 26 of Section V is telemetered to the computer and stored for processing.

The physical description of the automatic monitoring stations is discussed in Section V. Data transmission, storage, compilation, and input to the CATAD control system are discussed in Section VII.

Station performance is maintained weekly, or oftener depending on the status of data collected by the computer; i.e., extreme temperatures indicating pump failure or very low DO reading, usually meaning probe failure. During high river flow and heavy sediment load, lines are often plugged with sand and silt, requiring more frequent cleaning. Every three or four weeks, reservoirs are cleaned of aquatic growth, algae, barnacles and mussels. Appendix F lists routine monitor cleaning procedures which assure good data continuity.

Temperature, conductivity and pH analyzers are calibrated monthly using standards. Winkler dissolved oxygen (DO) samples are collected and analyzed in the monitor "mini-lab" weekly, depending on probe condition. Titrated values are compared with analyzer readings when samples are drawn. Minor probe drift adjustments are usually required.

SECTION X

DISCUSSION OF RESULTS

INTRODUCTION

The previous sections of this report have concentrated on physical aspects and development of the CATAD project. Two big questions remain. What does it accomplish? How much does it cost?

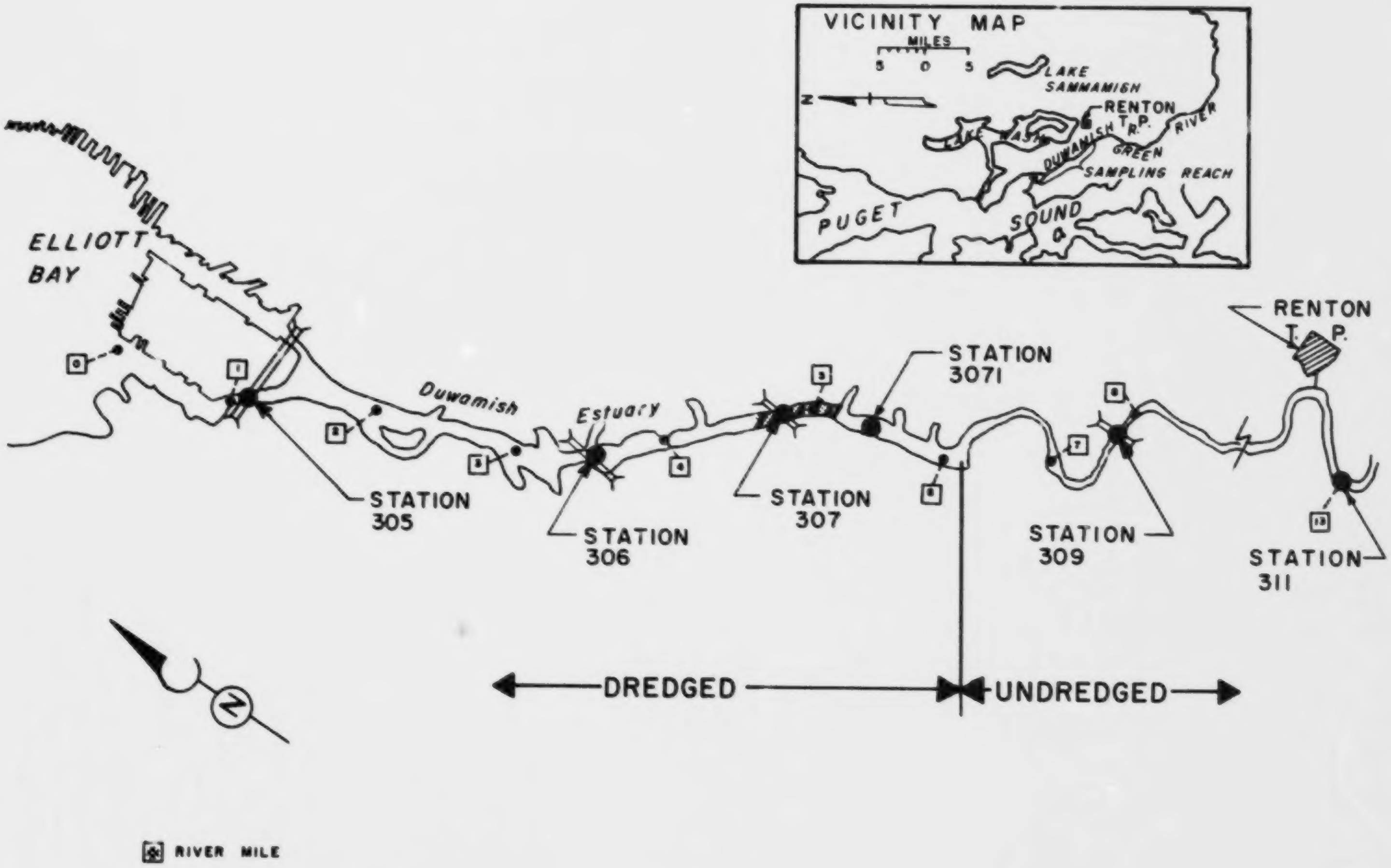
These questions are answered in the remaining two sections of this report. This section discusses CATAD project performance as reflected by water quality improvements and changes in overflow quality and quantity discharged to the receiving waters. The section is organized in the same sequence as Section IX which outlined the scope of the various water quality studies comprising the total project.

RECEIVING WATER

Receiving water quality is examined by reviewing the automatic monitor data from the Duwamish River and the bacteriological data from nearly all water bodies bordering the city. Small scale studies of river bottom sediments and aquatic life have not been sufficient to justify any major conclusions.

Monitor Data Analysis

Comprehensive data generated by the automatic monitor system provides an excellent opportunity to view long range effects of interception and regulation in the biologically and chemically critical Duwamish Estuarine environment. The estuarine environment has particularly critical dissolved oxygen (DO) problems because the saltwater wedge beneath the fresh surface waters continually transports settleable organic solids from the surface back upstream where they accumulate until periods of very high flushing occur. Consequently, in heavily loaded estuarine environments, the greatest fluctuations, hence the greatest stresses, occur near the head of the major salinity wedge between the bottom and surface DO concentrations. The two automatic monitoring stations best located for monitoring this condition in the Green-Duwamish Estuary are the 16th Avenue South station at the surface and bottom, and the Spokane Street location at the surface (Figure 74). The shaded portion is the area of critical DO fluctuation. Spokane Street bridge surface DO values were also included because they might better reflect the impact of fresh water storm drainage overflows on immediate DO suppression.


VICINITY MAP
MILES
5 0 5
N
LAKE SAMMAMISH
RENTON T.P.
RIVER
GREEN
DUWAMISH
LAKE WASH.
SAMPLING REACH
PUGET
SOUND
ELLIOTT BAY
Duwamish
Estuary
STATION 305
STATION 306
STATION 307
STATION 3071
STATION 309
STATION 311
RENTON T. P.
DREDGED
UNDREDGED
N
RIVER MILE

MAP OF DUWAMISH MONITORING STATIONS

FIGURE 74

STATION LOCATIONS

CATAD regulator system operation is based on the premise of overflowing first into Puget Sound and then, as necessary, into the upper estuary. Since interception and regulation in the Duwamish Estuary, progressively higher minimum and average DO values have been observed.

The maximum and minimum weekly values are plotted for the years 1969 and 1972 at the Spokane Street monitor for surface values, and at 16th Avenue South monitor for surface and bottom dissolved oxygen (Figure 75).

The improved DO trend at both the 16th Avenue South and Spokane Street monitors was apparent between the years 1969 and 1972. The hydrological data in Figure 76 shows significant river flow increases in 1971 and 1972, but not in 1973. In Figures 77 and 78, plots of surface and bottom minimum and maximum temperatures between 1969 and 1972 show little change. This data might indicate that improved DO conditions in the river resulted from higher flushing; however, when the low runoff 1973 monitor data is compared with 1969 data, it is nearly always higher than the same time period in the earlier year (Figure 79).

To clarify the DO trends, portions of the 1969 and 1972 data with apparent linear trends (May 12 to June 25 and September 15 to December 15) were selected. This data was statistically compared using analysis of variance. The results of these analyses indicate a statistically significant increase in DO with time (see Table 20).

Bottom Sediments

Benthic deposition in the lower Green-Duwamish Estuary has been studied since 1963. In this dredged section of the lower river, significant decreases in sediment chemical oxygen demand (COD) have been recorded between December of 1968 and 1971 (see Figure 80). This was partly attributed to diversion of the Diagonal Treatment Plant flow to the West Point Treatment Plant and to nearby land filling which produced observable quantities of sand erosion settling in the mid-channel sampling site. Since that time, however, further COD reductions have been recorded through most of the lower estuary for December. Contrary to the continuing decline, the June, 1973, observations averaged slightly higher. This may reflect the difference between summer and winter flushing. Additional urban storm drainage data is needed to understand the role of stormwater as a possible flushing mechanism in the lower estuary.

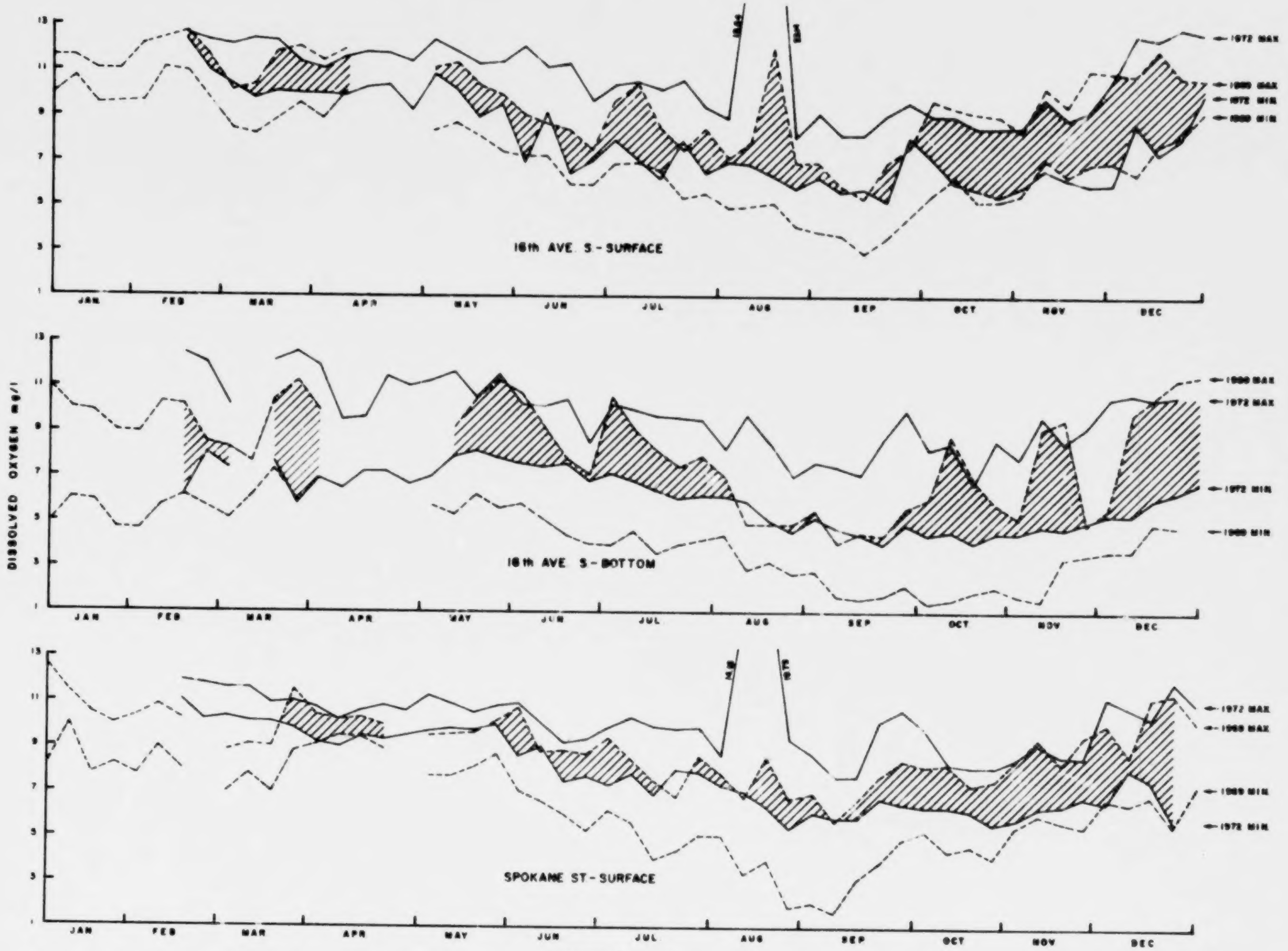


FIGURE 75

GREEN-DUWAMISH RIVER DISSOLVED OXYGEN RANGE

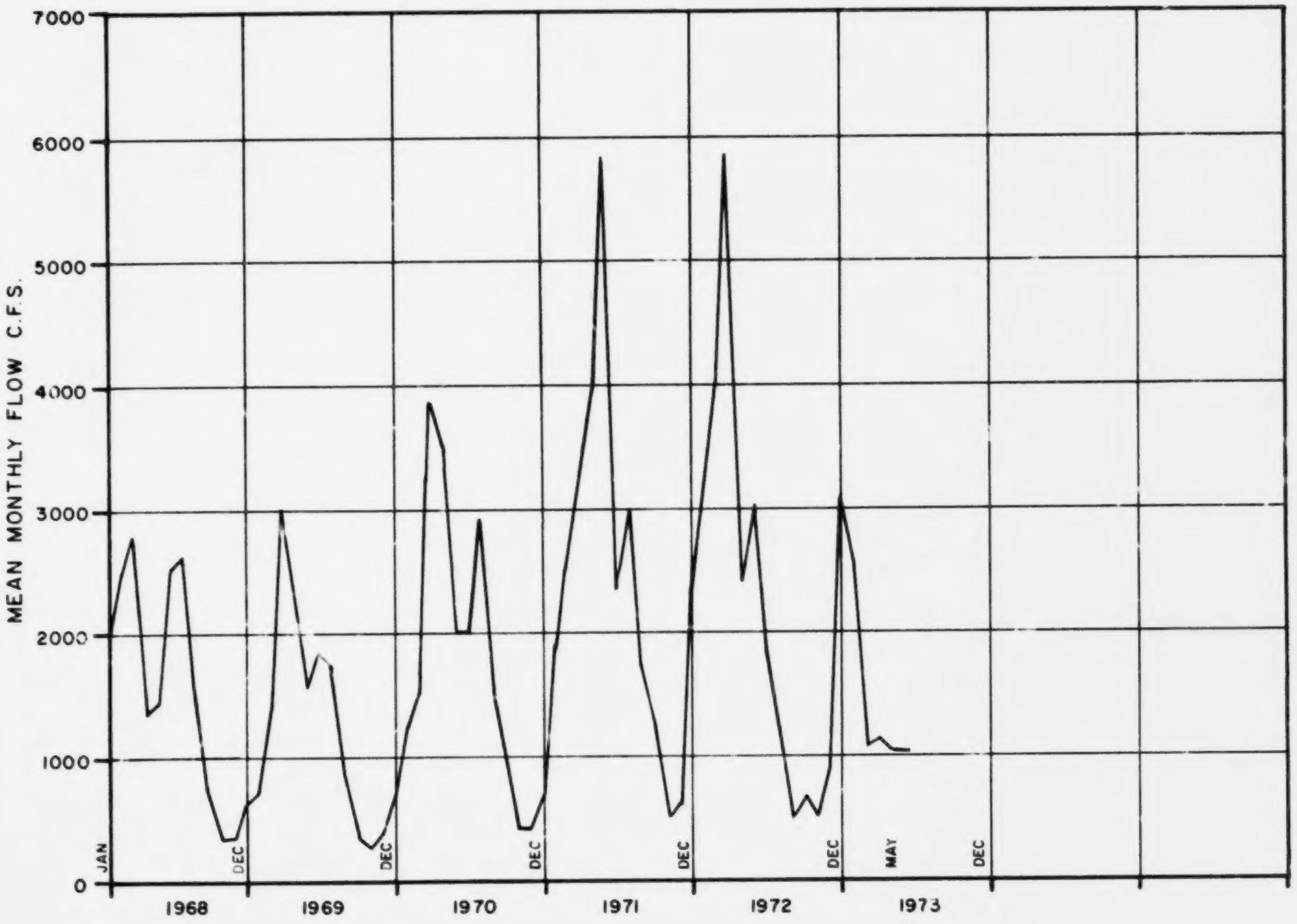


FIGURE 76

DUWAMISH RIVER FLOW

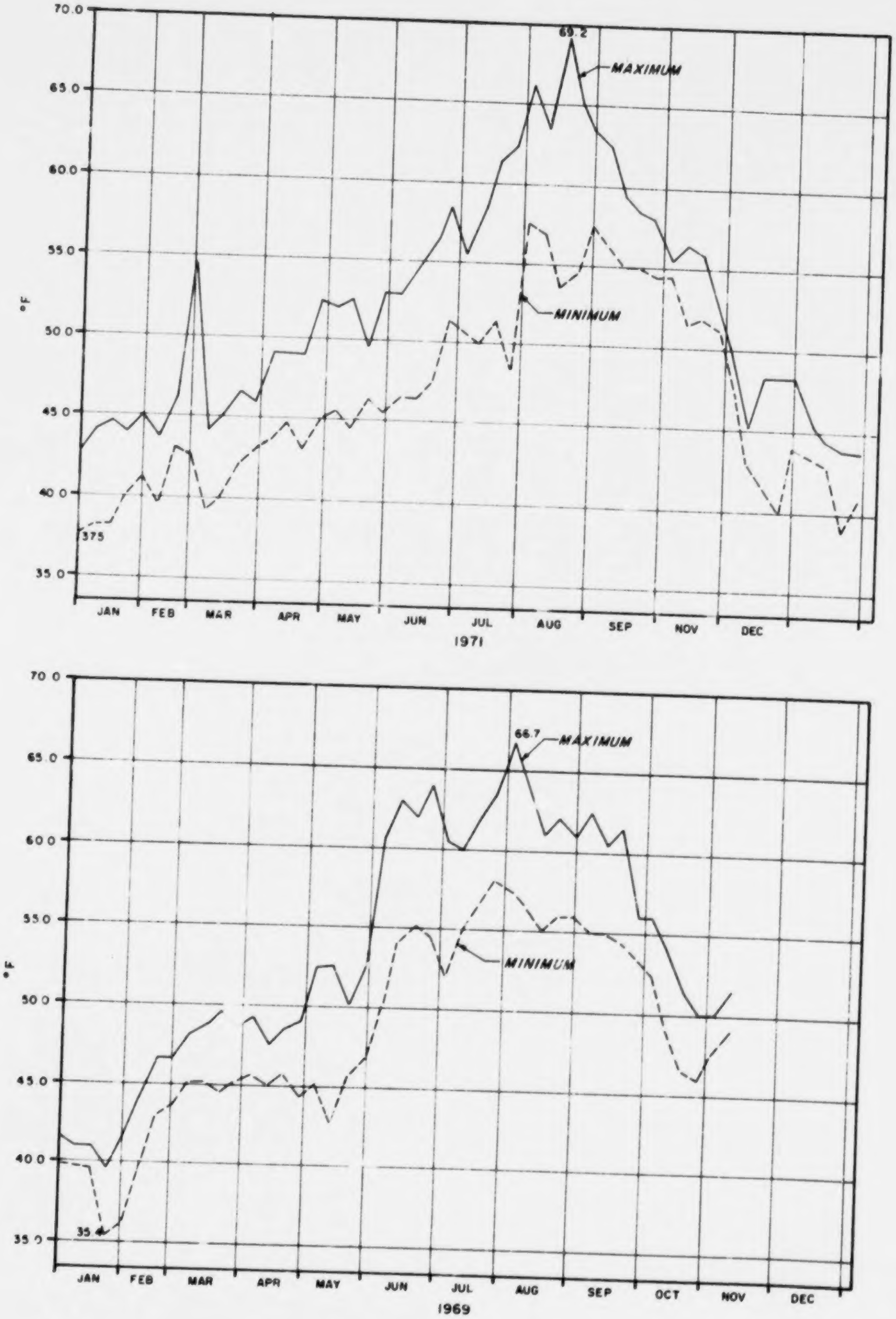


FIGURE 77

GREEN-DUWAMISH RIVER TEMPERATURE RANGE
AT 16TH AVENUE SOUTH, SURFACE

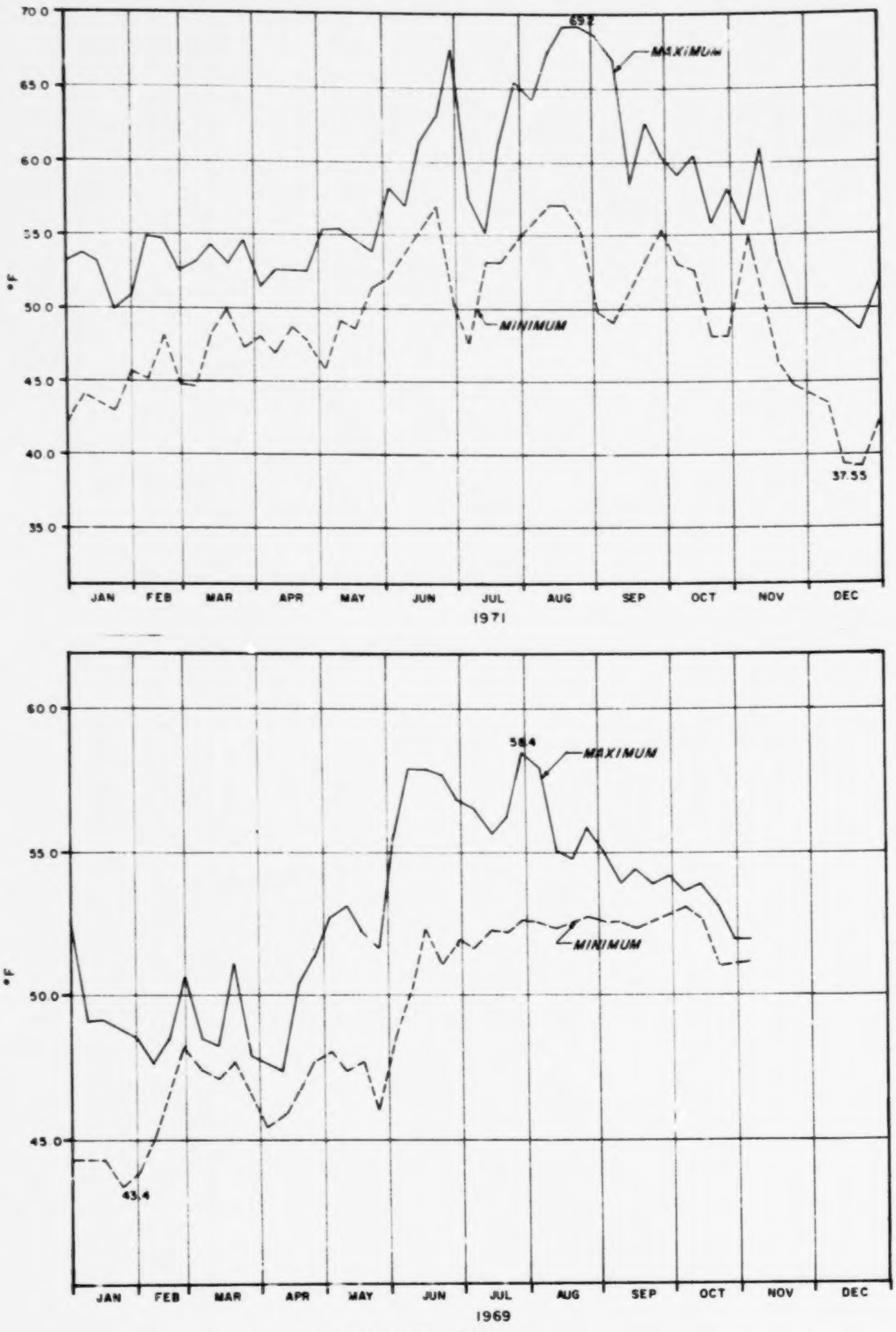
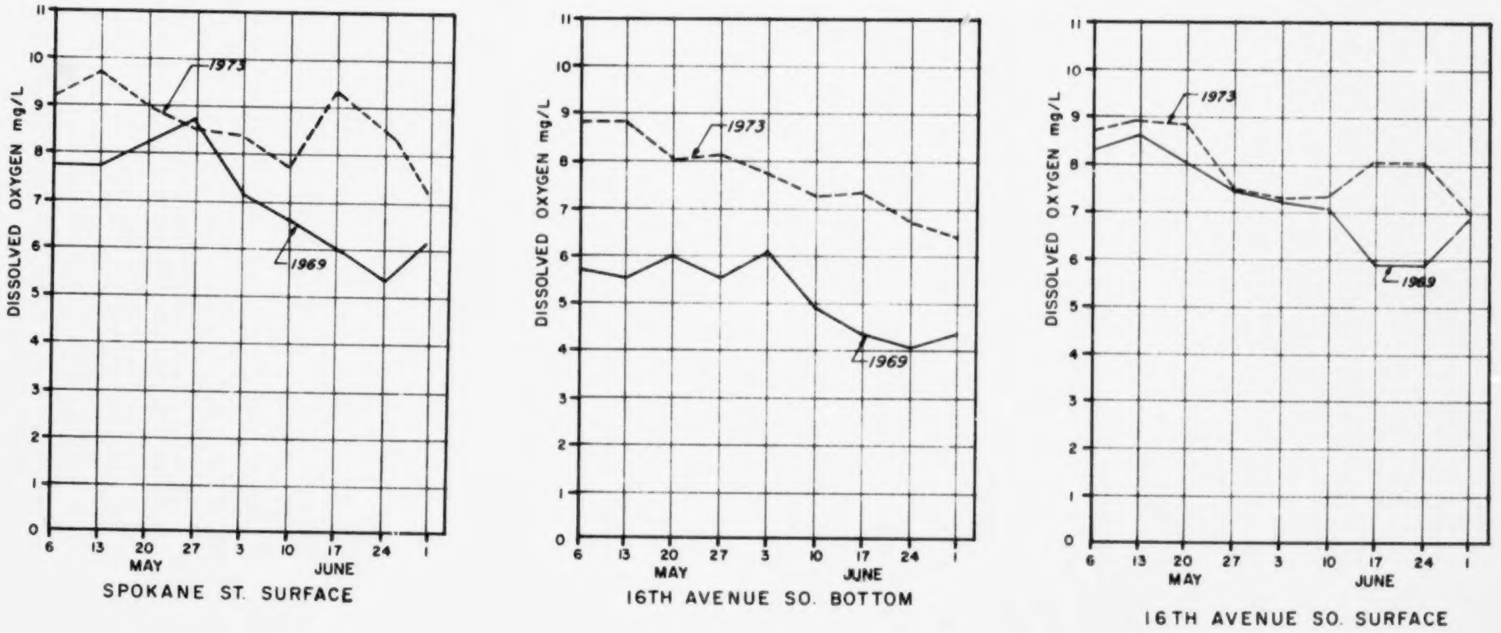


FIGURE 78

GREEN-DUWAMISH RIVER TEMPERATURE RANGE
AT 16TH AVENUE SOUTH, BOTTOM



SPOKANE ST. SURFACE

16TH AVENUE SO. BOTTOM

16TH AVENUE SO. SURFACE

FIGURE 79

GREEN-DUWAMISH RIVER MINIMUM DISSOLVED OXYGEN

Table 20 - DUWAMISH RIVER AUTOMATIC MONITOR ANALYSIS OF VARIANCE ON DISSOLVED OXYGEN DATA

	Sample Variation	Degrees of Freedom	Sum of Squares	Mean Square	
16th Avenue Surface Spring (5/12 to 6/25)	Between	1	59.0	59.0	F=59.38>5.29
	Within	78	77.5	1.0	
16th Avenue Surface Winter (9/15 to 12/15)	Between	1	9.5	9.5	F=8.34>5.15
	Within	92	104.3	1.1	
16th Avenue Bottom Spring (5/12 to 6/25)	Between	1	85.3	85.3	F=94.65>5.29
	Within	78	70.3	0.9	
16th Avenue Bottom Winter (9/15 to 12/15)	Between	1	121.0	121.0	F=432.44>5.15
	Within	92	25.7	0.3	
Spokane St. Surface Spring (5/12 to 6/25)	Between	1	20.5	20.5	F=22.99
	Within	78	69.7	0.9	
Spokane St. Surface Winter (9/15 to 12/15)	Between	1	42.8	42.8	F=48.66>5.15
	Within	92	80.9	0.9	

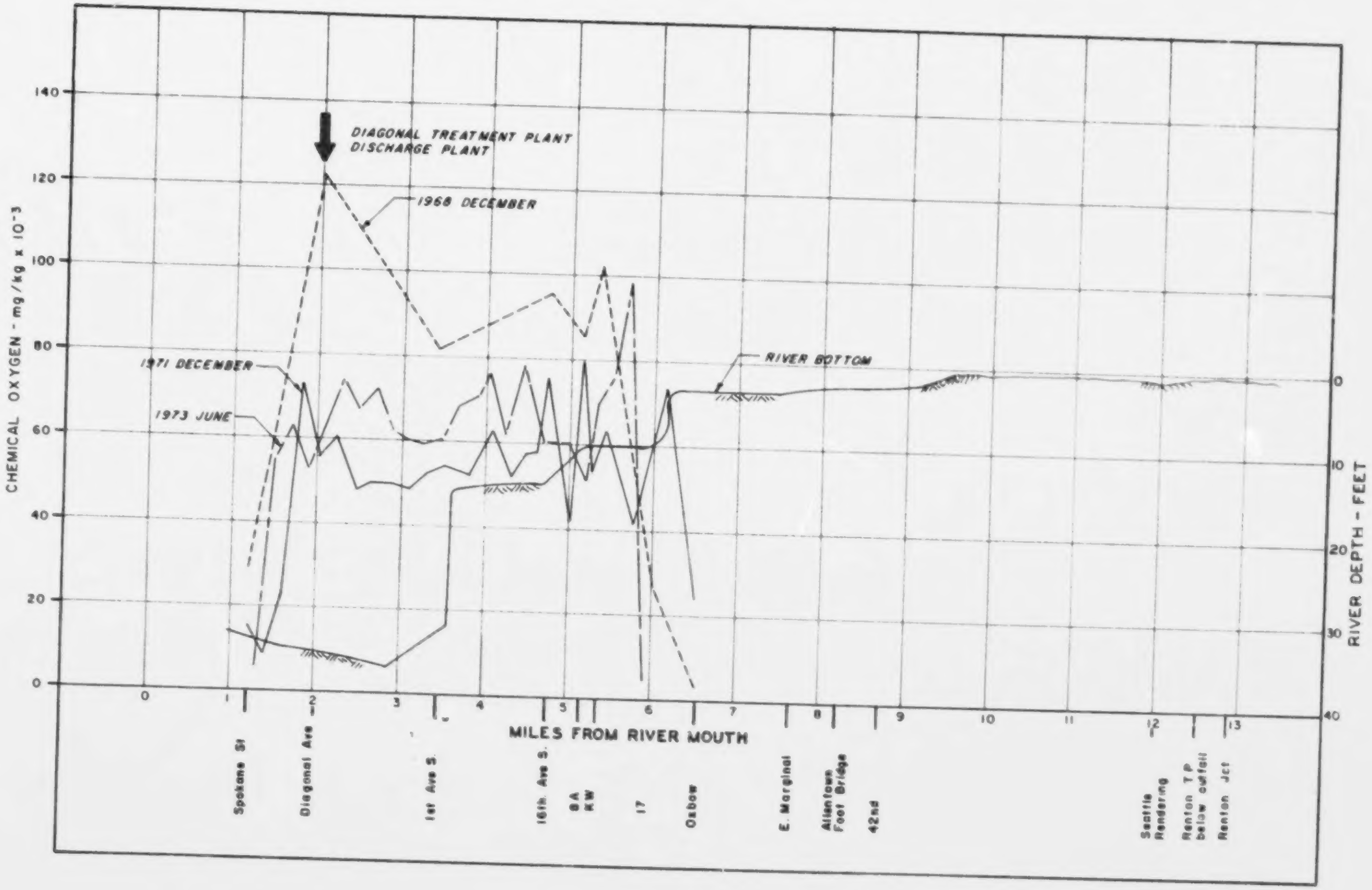


FIGURE 80

GREEN-DUWAMISH RIVER BOTTOM CHEMICAL OXYGEN DEMAND

Aquatic Life

The Green-Duwamish River uniquely exemplifies the feasibility of maintaining adequate water quality for fisheries resources in a highly industrialized metropolitan area. Data from the Washington State Department of Fisheries, Green River Hatchery, shows that adult salmon returns to the hatchery have been more than adequate to maintain significant runs of Chinook and Coho salmon in the river system (see Table 21). Although the Coho salmon data declined in 1972, scientists from the Washington State Department of Fisheries attributed this decline to:

Table 21. ADULT SALMON RETURNS[a]

YEAR	CHINOOK SALMON	COHO SALMON
1967	5,038	12,736
1968	8,114	50,856
1969	6,650	45,414
1970	10,714	70,868
1971	9,887	21,174
1972	6,828	9,076

[a] To Green River Fish Hatchery

1. A poor wild run of salmon placing greater demands on hatchery runs by sport, commercial and Indian fisheries
2. Reduced hatchery production because of budget cutbacks
3. Changes in fishery management to harvest as many of the surplus fish as possible.

A comparison of trawl catch results in the Duwamish River between the pre-sewer outfall diversion period (1967-68) and the post-sewer diversion period (1970-71) suggests an increase in the English sole population (see Table 22). The reasons for the decreased catch between 1970 and 1971 are not completely known, but may be partly attributed to natural population fluctuations. For example, the sand sole Psettichthys melanostictus, a bottom fish not previously captured in the Duwamish Estuary, was a common species during the post-diversion period. This species diversification suggests that the increase in dissolved oxygen enabled this species to survive in the Estuary.

Table 22. TRAWL CATCHES OF ENGLISH SOLE IN GREEN-DUWAMISH RIVER[a]

YEAR	1ST AVENUE SOUTH	16TH AVENUE SOUTH	STATION KW
1967	8.7	7.0	0.4
1968	15.5	2.4	0.4
1969	10.9	9.2	3.9
1970	27.8	45.5	8.8
1971	11.8	11.4	3.2

[a] Average for each year

Results from these and other studies demonstrate that removal of raw and treated waste discharges to the lower Duwamish River Estuary has improved water quality thereby ensuring continued growth and survival of salmon and other aquatic life.

Bacteriological

Bacteriological analysis results presented in the Interim Report (12) recorded striking improvements in total coliform counts between 1968 and 1970 in Elliott Bay. The improved quality was attributed to the diversion of several large raw sewage outfalls to the West Point Treatment Plant. When the 1971 and 1972 results are graphically compared with the previous median total coliform counts (see Figure 81), all the 1971 and 1972 results are below the water quality standards for inshore Elliott Bay. The improving trend between 1970 and 1972 is self-evident. Comparisons of median total coliform counts before and after CATAD control became operational are shown in Table 23. Seven of the nine stations com-

Table 23. MEDIAN COLIFORM COUNTS ELLIOTT BAY SHORE STATIONS

Station Number	Median Total Count per 100 mls 4/71 to 3/72 (pre-CATAD)	4/72 to 3/73 (post-CATAD)	Months that counts were lower
230	160	97	10 of 12
231	180	90	9 of 12
232	200	160	7 of 12
233	490	390	7 of 12
234	560	380	5 of 12
235	310	140	9 of 12
236	360	180	9 of 12
237	51	48	5 of 12
238	24	35	7 of 12

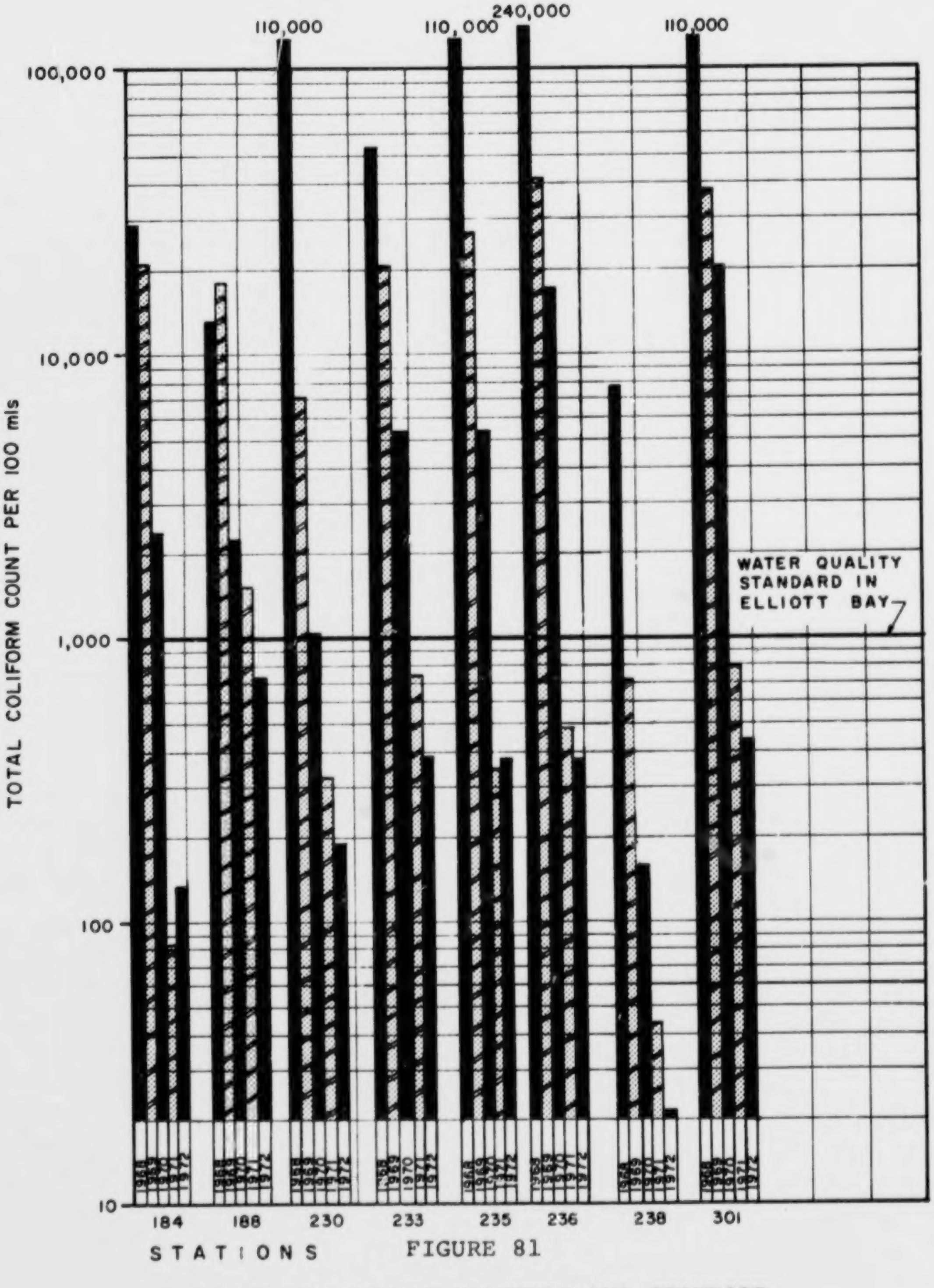


FIGURE 81

ELLIOTT BAY COLIFORM LEVELS AND STANDARD pared showed improving trends. Continued monitoring will show whether this is a real improvement or just a small difference in annual counts.

In the east and west waterways of the Duwamish River, median total coliform counts are hardly improved (see Table 24).

Table 24. MEDIAN COLIFORM COUNTS - DUWAMISH ESTUARY

Station Number	Waterway	Median Total Count per 100 mls 4/71 to 3/72 (pre-CATAD)	4/72 to 3/73 (post-CATAD)	Months that counts were lower
301	East	370	720	6 of 12
302	East	640	800	6 of 12
303	East	950	880	6 of 12
304	East	2600	1400	7 of 12
305	West	2300	2200	7 of 12

The reduction in maximum monthly counts (see Table 25) at Stations 304, 305, 306 and 307 in the Duwamish, upstream from major shipping activity, show a distinct improvement, particularly during summer low flow months when CATAD better utilizes storage capacity. When coliform count at Station 305 in the lower Estuary is compared with count from the upstream Station 315 in the Green River above the area affected by CATAD, decreased estuarine contamination can readily be seen between 1968 and 1972 (see Figure 82).

Low monthly median total coliform offshore counts in 1971 and 1972 (see Table 26), do not fully reflect an improving trend since only 27 of 48 months are lower. The offshore data may reflect background variation not directly related to the CATAD overflows.

The Lake Washington Ship Canal, Lake Union, and Portage Bay are all heavily used recreational areas. While regulator overflow sampling was not planned for this part of the system, several significant changes have taken place. Cleaning the Montlake siphon, Fremont siphon reconstruction, and construction of the Dexter Avenue regulator have all occurred in the last three years. The total coliform counts between 1970 and 1972 for 14 stations during either April to September or July to September, show substantial improvements (see Figure 83). These improvements partly reflect the 1972 CATAD efforts to utilize storage in the large Lake City tunnel, thereby relieving hydraulic loading on the Fremont siphon and averting possible back-up and overflow from Montlake siphon upstream relief points.

Table 25. MAXIMUM COLIFORM COUNTS IN DUWAMISH RIVER, EAST AND WEST WATERWAY

Month	Maximum Total Coliform/100-mls.													
	301		302		303		304		305		306		307	
	1971	1972	1971	1972	1971	1972	1971	1972	1971	1972	1971	1972	1971	1972
April	2900	780	3100	1300	3100	1100	6400	3300	6800	680	5800	3800	5100	3200
May	1600	1600	3000	660	3300	3000	4700	2500	7500	1900	2000	1600	3900	860
June	1200	2900	1400	3400	1700	8200	7100	4200	5100	2300	6400	3200	3600	2300
July	1700	8400	20	7900	10000	3800	58000	4600	16000	4900	21000	3700	2800	5100
August	740	440	5000	460	2200	31000	11000	26000	240000	12000	13000	7000	60000	5300
September	1200	2300	2000	2100	4500	2300	3900	18000	1200	12000	7400	9100	27000	8500
October	22000	4100	21000	1900	11000	2800	7900	3400	14000	3800	4600	2500	4200	8000
November	1500	26000	2200	1600	2900	1700	5200	27000	1600	4800	3600	11000	2200	4100
December	4500	7800	5300	8800	2800	6000	4800	6400	1200	3800	1200	2200	1200	2800
January	2000	1700	2700	1400	2800	1200	2400	2600	2500	660	2000	2800	2100	3200
February	2300	1700	2000	2000	580	1700	2500	1900	2200	740	2200	820	1600	330
March	7000	400	9200	300	5600	680	5400	1700	2500	2400	2000	3700	2200	1300

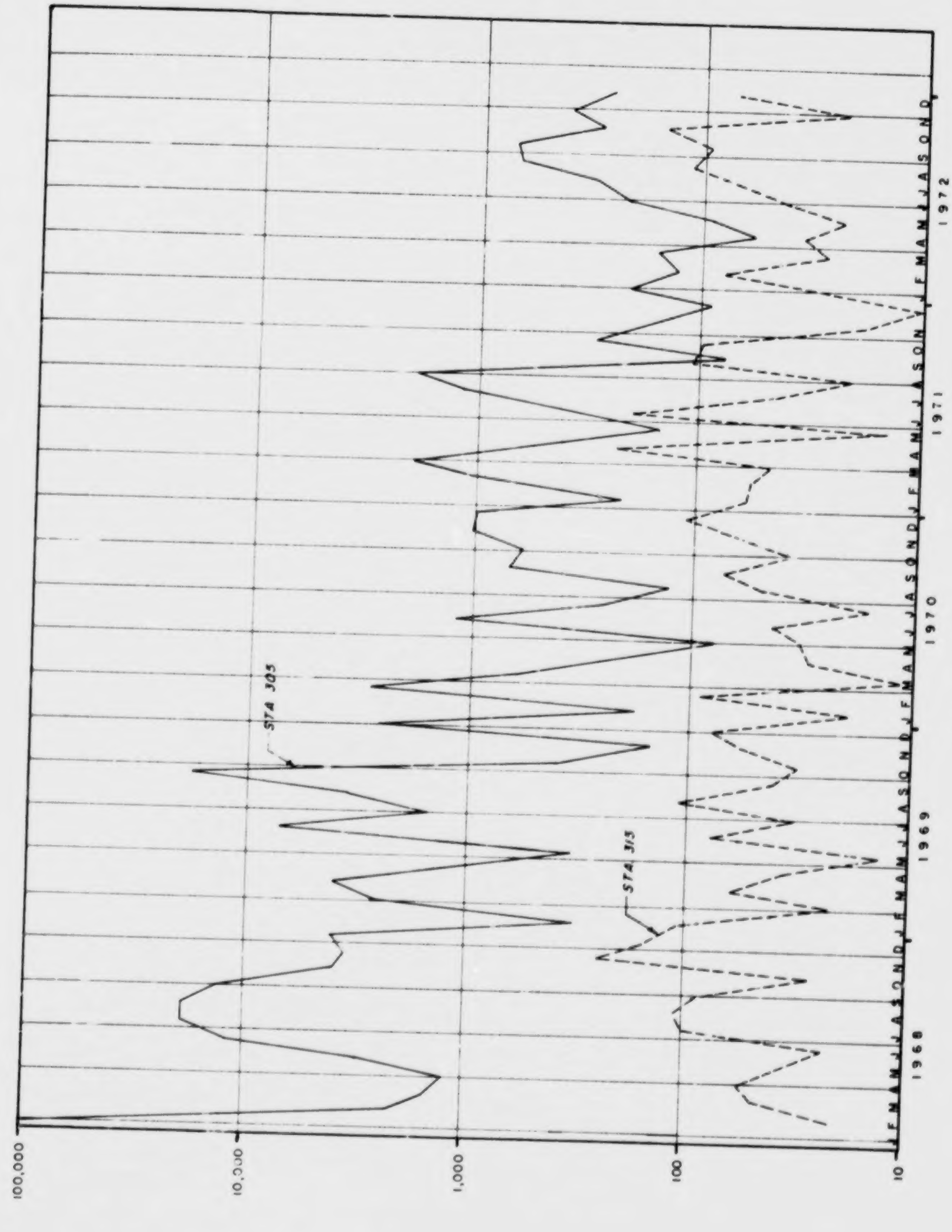


FIGURE 82

DUWAMISH RIVER COLIFORM COUNTS

Table 26. 1971-1972 ELLIOTT BAY MEDIAN TOTAL COLIFORMS/100 mls ONE METER DEPTH

MONTH	STATION NUMBER							
	181	182	183	184	188	189	1741	195
April	20-20	20-20	55-54	23-69	50-2400	70-90	20-50	20-910
May	20-20	57-110	23-94	23-94	280-550	20-150	20-130	20-1300
June	75-20	270-20	320-20	320-20	1300-70	150-20	46-20	20-20
July	20-20	25-20	40-26	170-40	---	---	---	---
August	20-20	20-20	20-20	230-20	---	---	---	---
September	20-20	65-20	41-20	130-140	1300-21	580-20	700-20	270-20
October	20-120	20-59	75-120	38-39	240-550	250-42	38-190	130-270
November	20-158	24-23	60-260	63-950	1800-3900	80-4100	64-130	88-2600
December	49-33	44-65	280-22	180-70	1400-480	270-75	310-43	250-500
January	30-20	65-22	58-39	110-53	150-170	48-160	20-50	52-250
February	40-[illegible]8	50-76	70-300	100-190	260-690	30-160	20-53	80-110
March	20-47	20-20	22-20	28-30	62-45	84-27	20-45	42-30

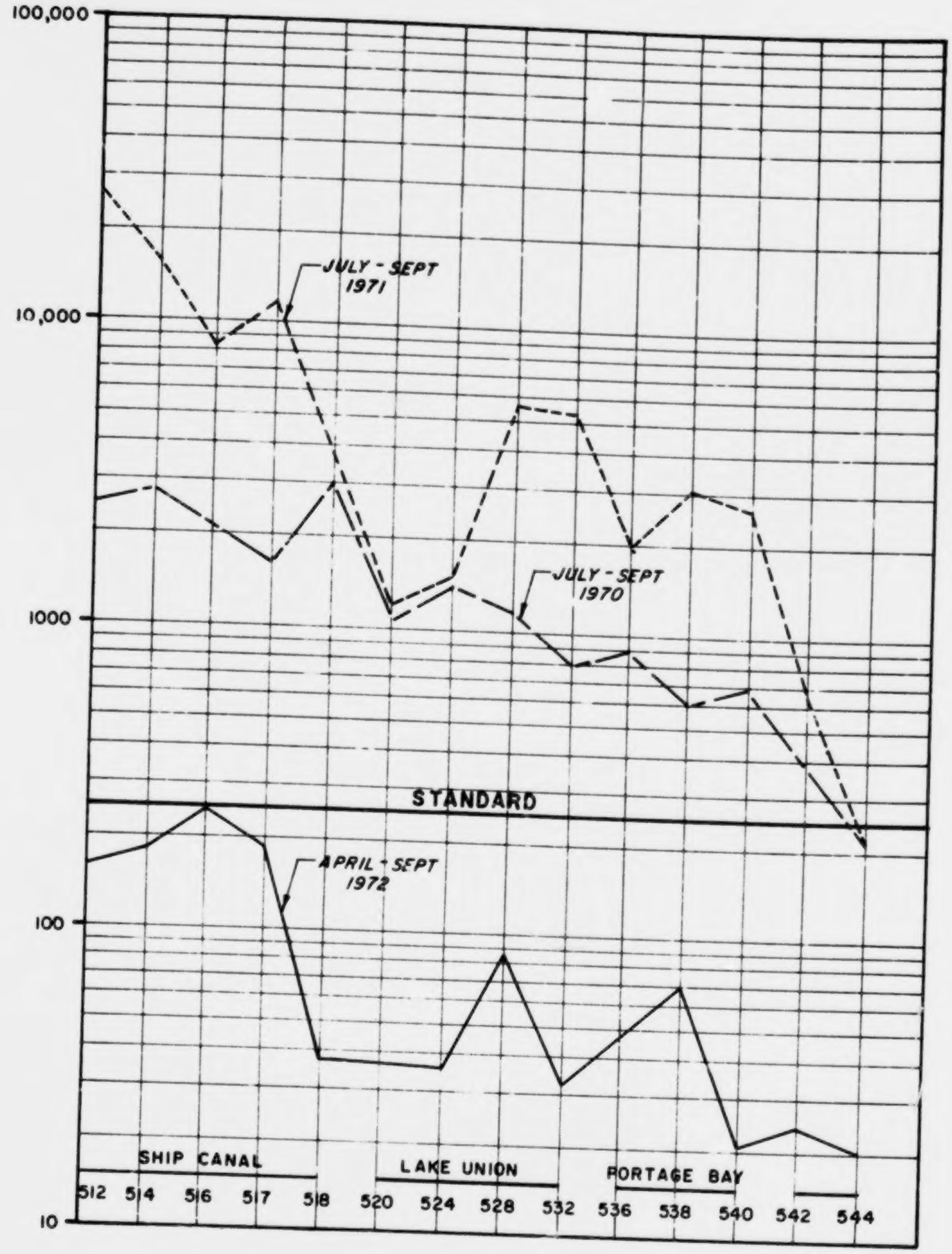


FIGURE 83

MEDIAN COLIFORM COUNTS,
LAKE WASHINGTON SHIP CANAL

RELATED STUDIES

The CATAD project concentrates on combined sewer problems resulting from excessive additions of storm runoff, so it is essential to study such effects separately. First, since rainfall patterns and intensities play a major role in overflow characteristics, storm analyses are evaluated. Much of the urban area is related to automotive uses, so runoff quality typical of streets, highways and parking areas is studied next. Finally, the effects of sewer separation are examined to distinguish changes in overflow quality or quantity from tributary areas which were partially separated during the course of this study.

Storm Studies

The evaluation of CATAD system performance through the demonstration grant period required a thorough analysis of rainfall patterns. Rainfall data from six gages in the Elliott Bay-Duwamish River region was collected and analyzed for the period November 1, 1969, through July 1, 1973. The data included one storm of 0.47 inch for a 60-minute period which, according to Figure 84, is a five-year storm. Average annual rainfall for the period was 38.25 inches, within the average of 30-40 inches (see Table 27). So it can be assumed that the collected rainfall data is representative. Total storm data, summarized in Table 27, shows that in the study period, storm activity for both total number of storms and inches of rainfall, was relatively normal with the following exceptions:

1. 1970 had a drier than normal summer season.

2. 1971 had more storms, and was somewhat wetter during summer but well within the norm.

3. 1973 had unusually light rainfall up to July 1 although the number of storms was normal.

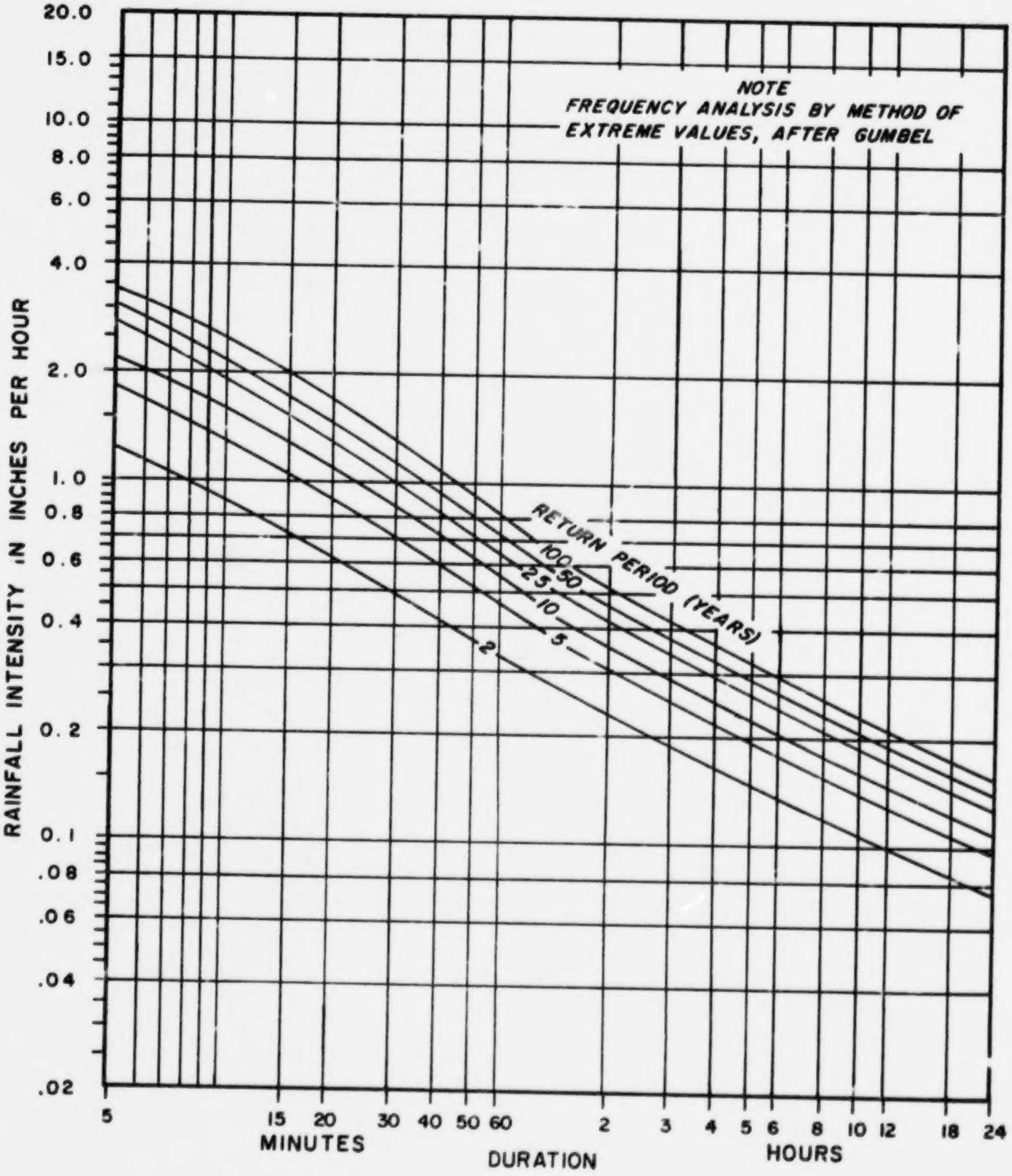


FIGURE 84

CITY OF SEATTLE RAINFALL FREQUENCY, INTENSITY, DURATION

Table 27. TOTAL ANNUAL STORM DATA[a]

Year	Item	Full Year	Half[b] Year	Summer[c] Season
1970	Storms	142	87	11
	Inches	37.21	18.22	1.54
1971	Storms	171	96	22
	Inches	37.16	20.46	3.64
1972	Storms	144	82	16
	Inches	40.38	22.75	2.38
1973	Storms	--	87	--
	Inches	--	9.33	--

---

[a] Note: Annual average 30-40 inches/year (43)
Summer average 2-6 inches/year

[b] January to June inclusive

[c] June to August inclusive

Average monthly rainfall patterns for the Seattle area are shown in Figure 85.

This section defines summer or recreational periods as those months averaging two inches of rainfall or less. This recreational period extends from May through September. A computer program was developed to analyze rainfall data for total accumulative rainfall maximum rates and average rates for various ranges as shown by sample tables presented in Appendix K. Although the demonstration grant sampling phase began in November, 1969, regulator and sampling unit construction was not complete until April, 1971. Comparisons of present overflow data with earlier data are inaccurate due to this missing information. However, the storm study includes all valid rainfall information for the entire period November, 1969, to July, 1973.

Table 28 compares storms during the demonstration grant period, compiled by averaging together data from all operating rain gages. The table shows no unusual change in storm patterns over the demonstration grant period. Total accumulative rainfall amounts, over the total period and for post-supervisory and post-auto control periods, show an average of 80 percent of storms is under 0.3 inch with a slight increase during post-supervisory control periods. Maximum rainfall rate distribution is even closer, with a variation

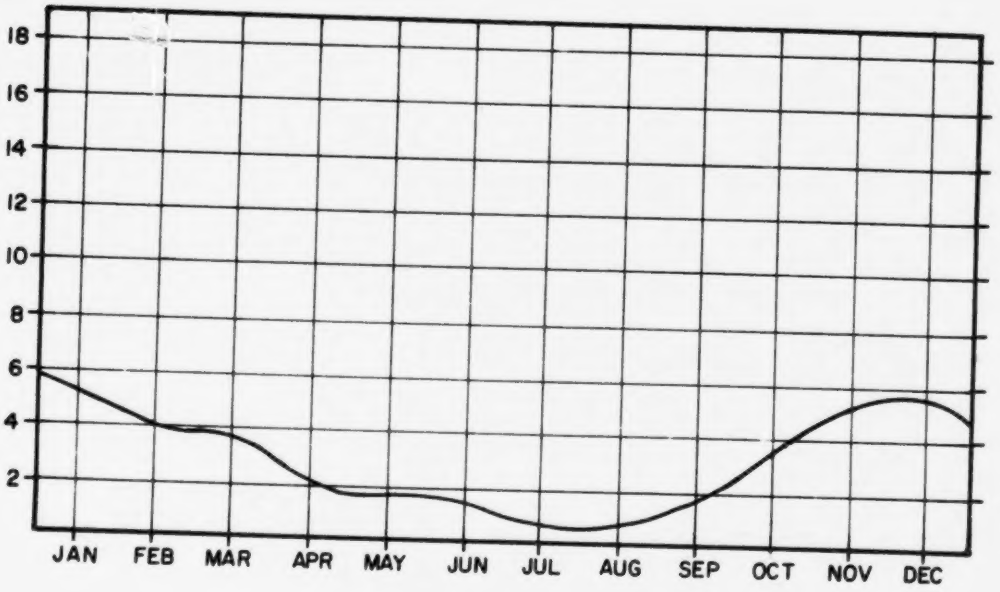


FIGURE 85

AVERAGE MONTHLY PRECIPITATION
CITY OF SEATTLE

of only three percent for all rates of 0.07 inch per hour or less during any of the three study phases. Average rainfall rates for storms of 0.05 inch per hour or less are essentially constant over the entire period and for each control phase.

During summer storm periods only, the number of storms which accumulated 0.3 inch of rainfall or less varied no more than seven percent over the entire period and for all study phases. Similarily, maximum rainfall rates and average rainfall rates were closely related for the entire study period and the individual control phases. The last column in the table indicates any significant changes in the percentage of summer storms versus total storms for the different project phases. Although a significant increase in summer storms is indicated during the post-automatic control phase, the data is biased by the fact that two of the three months were defined as summer months.

An alternate rainfall data review is shown in Figure 86. The percentage of summer storms versus total storms for each range of total rainfall, maximum rainfall rate, or average rainfall rate is plotted for the entire study period and for each control phase. This figure indicates a greater percentage of storms occurring in the lower ranges of total rainfall and maximum or average rainfall rates during the supervisory and automatic control phase of the study. This apparent distribution change during the last fifteen months of the study as compared to the total forty-five month period occurred simultaneously with an apparent increase in percentage of summer storms. The 20 percent increase in summer storm activity shown in Table 28 is partly offset by the lower number of more intensive storms which occurred after implementation of CATAD supervisory and automatic controls.

Table 28. COMPARATIVE RAINFALL DATA CITY OF SEATTLE

Time Period	Annual Percent			Summer Percent[a]			Pct.	Pct.	Corrected
	≤.3 Inch Total Rain	≤.07 in/hr. Max. Rate	≤.05 in/hr. Avg. Rate	≤.3 inch Total Rain	≤.07 in/hr. Max. Rate	≤.05 in/hr. Avg. Rate	$\frac{\text{Summer St.}}{\text{Year St.}}$	$\frac{\text{Summer Mo.}}{\text{Year Mo.}}$	Pct. $\frac{SS}{YS}$
4 years 11/69 - 7/73	78	74	88	83	79	91	22	40	23
Pre-CATAD 11/69 - 4/72	76	73	87	83	76	89	23	34	28
Post-CATAD 4/72 - 7/23	82	77	88	90	84	94	28	50	23
Post-Auto 4/73 - 7/73	83	77	95	80	80	95	67	67	42

[a] Summer, being defined as May to September

[b] Corrected = Pct. $\frac{\text{Summer Storms}}{\text{Year Storms}} \times \frac{\text{Pct. Summer Months (Norm.)}}{\text{Pct. Summer Months (Period)}}$

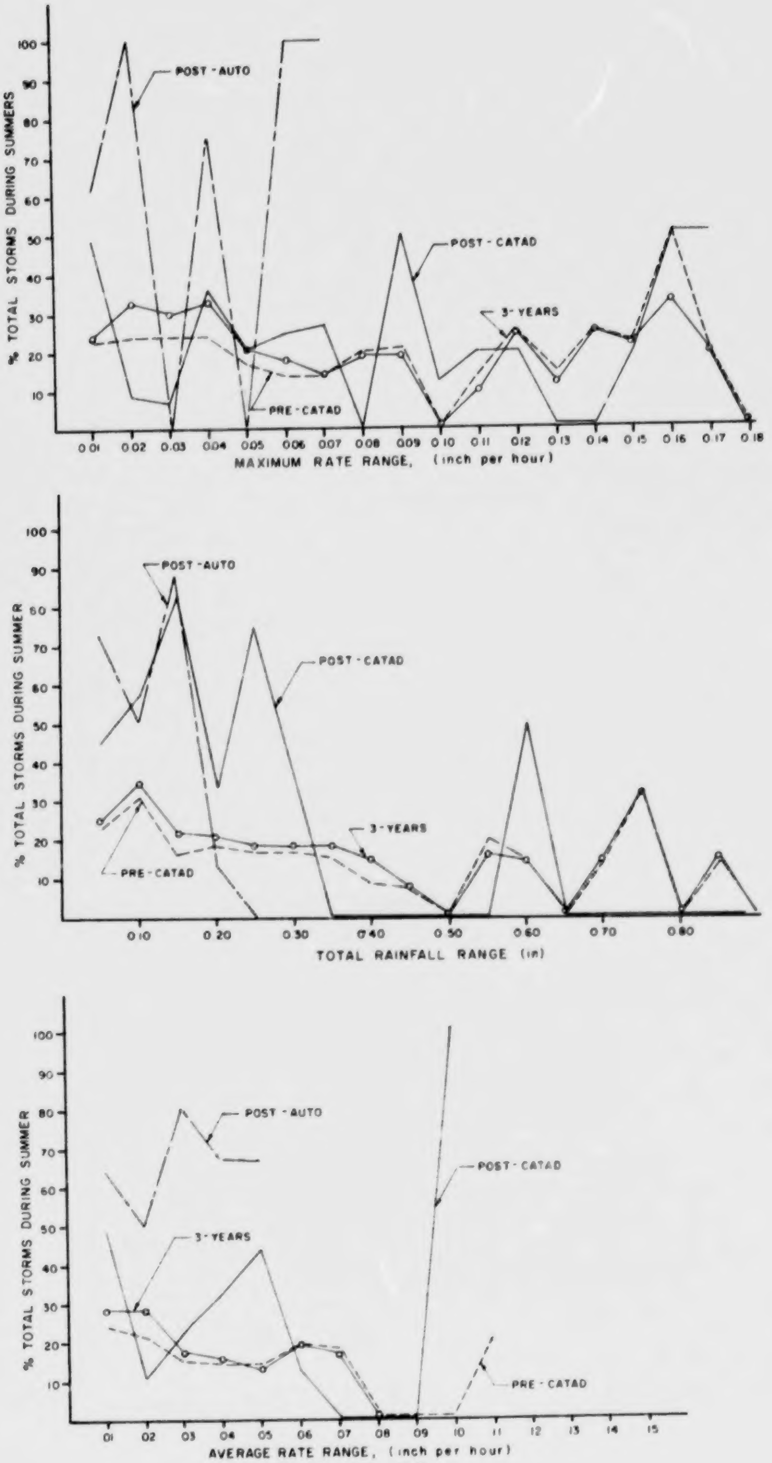


FIGURE 86

SUMMER RAINFALL DISTRIBUTION

It was somewhat difficult to analyze storm patterns and their effect on overflows for this demonstration grant. Storm patterns might be divided into three groups:

1. An area-wide or uniform storm which is nearly the same for all time periods at each analyzed gaging station
2. A traveling or frontal storm which proceeds from one direction to another
3. A pocket or localized storm which occurs or is much heavier at one or two gaging stations.

Table 29 shows storm pattern variations for the project control phases and seasons. Only storms of 0.05 inch or greater are included. All control phases show a pattern change from frontal winter storms to localized summer storms. The post-CATAD and post-auto phases both indicate an improved ratio of the theoretically more-controllable local and frontal storms compared to the less-controllable uniform storms.

Highway Runoff

Metro assisted the Washington State Department of Highways in preparing environmental impact statements for interstate freeway I-90. Samples were drawn directly from roadway runoff before it entered either storm drain or combined sewer. The findings of these efforts are summarized below.

Suspended solids, BOD, COD and oil concentrations appeared relatively high while nutrient levels were comparable to those found in urban drainage samples. Lead and zinc were the major heavy metals and were found principally in the solids portion of the sample.

An example of pollutant concentration and loading found in the runoff from the I-90 corridor is presented in Tables 30 and 31. This data was obtained from the South Bellevue interchange during Phase I of the study. Differences in pollutant concentration and loading for different geographical areas may have been due to differences in road surface, weather, type of nearby soils which may be washed or windblown onto the roadway, types of vehicles, and average vehicle speed.

Table 29. STORM PATTERN VARIATIONS[a]

	Annual			Summer		
	Uniform	Frontal	Local	Uniform	Frontal	Local
Total Period 11/69 - 7/73	219 (36%)	167 (28%)	218 (36%)	48 (37%)	19 (15%)	62 (48%)
Pre-CATAD 11/69 - 4/72	165 (38%)	118 (27%)	147 (34%)	36 (44%)	13 (16%)	33 (40%)
Post-CATAD 4/72 - 7/73	54 (31%)	49 (28%)	72 (41%)	12 (25%)	6 (13%)	29 (62%)
Post-Auto 4/73 - 7/73	2 (8%)	6 (24%)	17 (68%)	2 (13%)	1 (7%)	12 (80%)

[a] Storms of 0.05 inch or greater total rainfall only.

Table 30. STORMWATER RUNOFF QUALITY SOUTH BELLEVUE INTERCHANGE

PARAMETER		MAXIMUM	MINIMUM	MEAN
Temperature, °C		8.2	4.0	6.0
pH		7.8	6.4	7.1
Conductivity, micromhos/cm		4500	48	500
Turbidity, JTU's		175	24	84
Settleable Solids, ml/l		2.7	0.1	0.4
Suspended Solids, mgs/l		1496	42	246
Volatile Solids, mgs/l		396	12	57
Total coliform, organisms/100 mls		14,000	20	650(1)
Fecal coliform, organisms/100 mls		2,200	20	50(1)
COD, mgs/l		433	30	123
Oil, mgs/l		96	0.0	14.9
BOD, mgs/l	(S)	42	5	13
Ammonia, mgs N/l	(S)	0.44	0.05	0.22
Nitrate-Nitrite, mgs N/l	(S)	1.85	0.30	0.75
Kjeldahl Nitrogen, mgs N/l	(I)	4.20	0.09	0.50
Phosphorus, mgs P/l	(S)	0.12	0.02	0.05
Phosphorus, mgs P/l	(I)	1.10	0.03	0.26
Lead, mgs/l	(S)	0.52	0.10	0.17
Lead, mgs/l	(I)	4.50	0.10	0.99
Zinc, mgs/l	(S)	0.64	0.005	0.059
Zinc, mgs/l	(I)	0.749	0.010	0.111
Copper, mgs/l	(S)	0.20	0.01	0.034
Copper, mgs/l	(I)	0.16	0.01	0.018
Cadmium mgs/l, Total		0.016	0.004	0.004
Chromium, mgs/l Total		0.01	0.01	0.01

(1) Median Concentration (S) Soluble (I) Insoluble

Table 31. LOADING FACTORS
SOUTH BELLEVUE AREA

Parameter		Loading Factors	
		mgs/m^2/day	mgs/m/vehicle
Suspended Solids		202	25.8 X 10^{-2}
Volatile Solids		47	6.1 X 10^{-2}
COD		135	17.4 X 10^{-2}
Oil		12.1	15.5 X 10^{-3}
BOD	(S)	9.0	11.6 X 10^{-3}
Ammonia as N	(S)	0.12	15.8 X 10^{-5}
Nitrate-Nitrite as N	(S)	0.44	55.4 X 10^{-5}
Kjeldahl Nitrogen as N	(I)	0.96	12.4 X 10^{-4}
Phosphorus as P	(S)	0.04	5.3 X 10^{-5}
Phosphorus as P	(I)	0.24	3.2 X 10^{-4}
Lead	(S)	0.12	1.6 X 10^{-4}
Lead	(I)	0.72	9.2 X 10^{-4}
Zinc	(S)	0.02	2.6 X 10^{-5}
Zinc	(I)	0.10	13.2 X 10^{-5}
Copper	(S)	0.01	13.2 X 10^{-6}
Copper	(I)	0.02	26.4 X 10^{-6}

(S) Soluble (I) Insoluble

Dispersion coefficients and dilution factors measured as a part of this study were used to recommend the best stormwater outfall sites for Lake Washington. These coefficients showed that the pollutants were dispersed rapidly in the receiving waters to levels within Washington State's established standards (44) or close to accepted criteria where specific standards are unavailable (45, 46). This dispersion was further confirmed by measuring receiving water quality during and after a typical runoff period.

In addition to measuring storm runoff pollutants from existing freeway facilities and projecting these values to future facilities and traffic increases, an attempt was made to evaluate the impact of highway construction. As expected, the major pollutants measured were solids and oil, with solids coming from large areas where ground cover was removed and oil from new asphalt paving. Streams adjacent to this type of highway activity are definitely effected by roadway drainage. Construction effects can be minimized by adopting improved pollutant control techniques (39).

In general, no significant water quality problems were indicated from the I-90 stormwater runoff discharge into major receiving water bodies, particularly Lake Washington. Cumulative effects were not investigated. Preventive measures such as sweeping and vacuuming should help alleviate problems caused by the two major freeway surface pollutants; solids and oils.

Sewer Separation and Urban Storm Drainage

The City of Seattle's combined sewer separation project increased the volume and frequency of stormwater discharge into Lake Washington. Evaluation of the separation program impact on water quality indicated the coliform organism concentration had diminished by a factor between 60 to 140 times, and a lower fecal to fecal strep ratio, indicative of non-human sources, was evident (12). Stormwater nutrient concentrations were lower than in the combined sewer, showing less potential for contributing to eutropnication. The nutrient concentration reductions varied by the following factors: 5 to 8 times for total phosphate, 1.3 to 2 times for nitrate, and 7 to 11 times for ammonia. Oxygen demand and solids were 2 to 5 times lower (12).

Despite the increased stormwater flow to the lake, total loading of the parameters under study indicated a significant loading reduction achieved by separation. The discharge factors in pounds/acre/year after separation for the various constitutents were as follows: BOD - 19.4; COD - 88; suspended solids - 72; NH_4 - 0.63; NO_3 - 0.46; and PO_4 - 0.70. This represents a decrease of 37 to 64 percent compared to the combined sewage overflow.

To determine the role of stormwater from combined sewer systems on water quality, preliminary data from Metro's urban storm drainage studies was reviewed. From a single storm in March, 1973, samples were collected from a residential (VR1), commercial (CBD-7), and parking lot area (SC-4). Water quality data from those samples are presented in Appendix L. In the area draining a large parking lot at the South Center shopping mall (south of the Norfolk St. Regulator), hydrolyzable phosphate, dissolved oxygen and total coliform lagged the peak rainfall by 15 minutes. Nitrate, lead, zinc, iron, oils, turbidity and solids peaked at the same time as the flow. Suspended solids, BOD, cadmium, chlorinity and Kjeldahl-nitrogen peaked 15 minutes before peak rainfall; while some parameters such as ortho phosphate and ammonia dropped and then stayed low. In the case of the residential area (VR2-1), the lag was not recorded for some parameters such as nitrate, turbidity, oils and COD; but the others, like the hydrolyzable phosphate and ortho phosphate, peaked before the rainfall did, suggesting that these parameters are initially concentrated (perhaps in the standing water in the pipes) and then readily flushed from the system.

Copper, lead, zinc, oils and chlorinity were highest from the parking area (SC-4), while turbidity, nitrates, phosphates and coliform were much higher in the residential area. COD's were similar for both areas.

The peak patterns for the water quality data from the central business district were more complex. The extremely high bacterial counts, phosphate and all metals but lead, suspended soilds, chlorinity, BOD and oils, clearly substantiate the potential of runoff from this combined system to degrade water quality (Appendix L). Rainfall during the analyzed storm was greater in the central area than the others observed, but many of the relatively high parameters were measured during a period of relatively light rain preceding the main storm. The capacity of the CATAD system to absorb light rains from the central business district where the greatest regulating effort is concentrated is consequently a significant step towards abating the water quality degradation which would otherwise occur with every rain. Establishing parameter loading values will depend on numerous storm intensity and antecedent rain periods being recorded and the resultant water quality data.

Tentative loading values for three storms in the 100-acre central business district are recorded in Table 32 along with values from one storm in the 150-acre separated residential community of Lake Hills. Curves of increased parameter loading with increased rainfall are suggested for relative loading of nitrite-

Table 32. LOADING (lbs/storm)

Station	CBD			Lake Hills
Date	3/10/73	3/16/73	6/6/73	3/16/73
Rain (Inches)	0.33	0.06	0.08	0.08
Suspended Solids	309.00	49.60	146.80	157.20
BOD	61.40	23.60	94.60	16.80
COD	233.60	87.50	191.80	---
NO_2-NO_3-N	0.72	0.14	0.49	1.22
Hydrol. PO_4	0.33	0.26	0.77	0.49

nitrate nitrogen, suspended solids and COD (see Figure 87). From the table, phosphate appears 1.6 times higher for the central business district during the one storm comparison. Nitrite-nitrate nitrogen, on the other hand, was 2.35 times higher from the residential area.

When these observations from the recently initiated urban storm drainage study are repeated in subsequent storms, it will be possible to anticipate loading changes from regulator overflows resulting from further separation.

Water quality data alone from the Norfolk Street Regulator between 1970 and 1972 indicates slight increases for settleable solids, suspended solids, volatile solids and phosphate, while BOD and COD concentrations appear similar and the ammonia and nitrite-nitrate nitrogen decreased (see Figure 88). This area was approximately 87 percent separated by 1972. The Norfolk drainage area did not respond with markedly larger nitrite-nitrate nitrogen, or phosphate decreases as the residential Lake Hills data suggests. Perhaps additional data from storm drainage studies will better demonstrate the effects of land uses and topographical configurations on storm runoff characteristics.

REGULATOR STUDIES

Paralleling the receiving water studies is a program of sample collection and data reduction related only to overflow events. In the early stages of this demonstration grant project, the requirement for precise and complete data was recognized and the semi-automatic equipment described in Section IX was installed. Overflow quality and quantity information provide a basis for evaluating

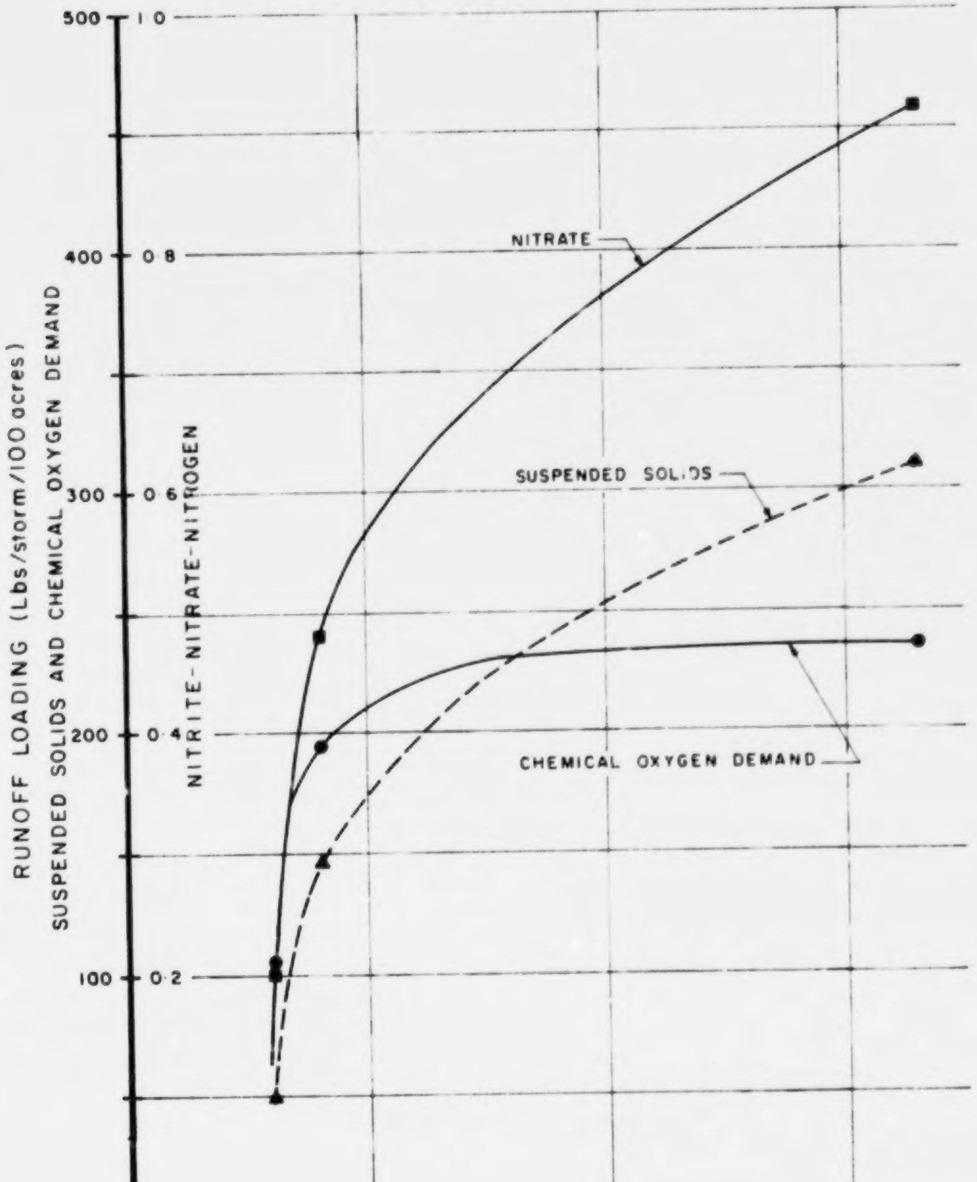


FIGURE 87

STORM DRAINAGE LOADING

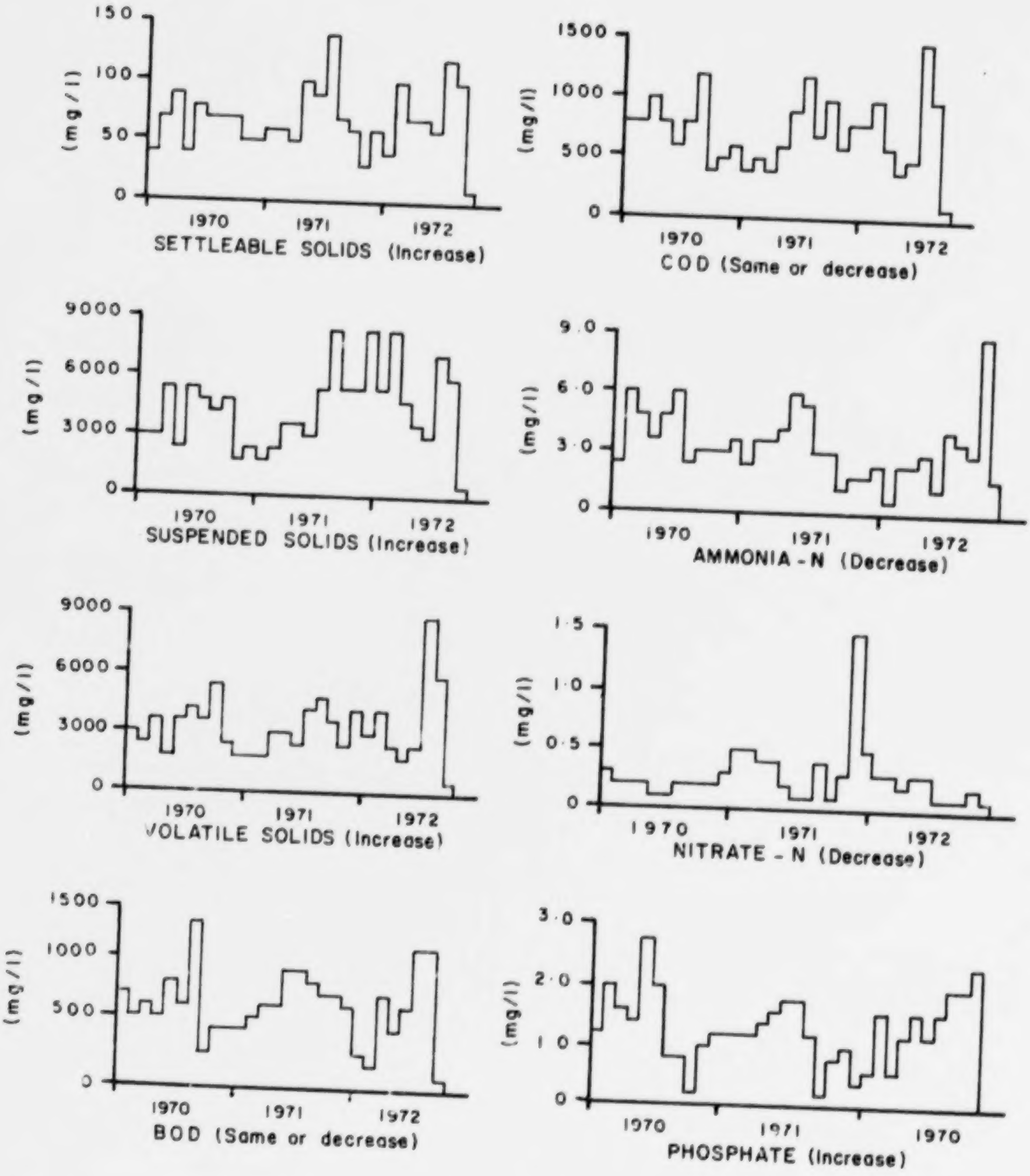


FIGURE 38

NORFOLK REGULATOR - LONG TERM OVERFLOW QUALITY receiving water loading as related to changes observed in the ongoing area-wide monitoring and for measuring performance of individual regulators and the entire system. A limited sampling program began in the summer of 1968. System-wide data was not available until April, 1972, the starting point for most of these studies.

Regulator Water Quality Analysis

Initial regulator data analysis included a general evaluation of each regulator station's performance relative to the area controlled, samples collected and relative frequency of overflows recorded. This data is presented in Table 33. The four most reliable station/sampler combinations were selected from Table 33 to represent the entire study area and smaller subareas which had undergone sewer separation.

Some stations seldom overflowed while others overflowed frequently with either high intensity and short duration, or moderate intensity and extended duration. This dissimilarity was attributed to the amount of storage available (see Figures 89 and 90). Sequentially sampled water quality and flow quantity were available for Denny Way-Lake Union, Connecticut Street, Hanford, Chelan Street, and Michigan Street regulators. The Hanford Street regulator serves a mostly hilly, residential area, 42 percent of which has been partially separated (27). Denny Way-Lake Union and Connecticut Street serve the central business district. Chelan Street and Michigan Street serve the flat south industrial area. The areas served vary in size from 1.17 square miles at Michigan Street to 6.3 square miles at Hanford Street (Appendix A).

The average of sequential water quality parameters vs. time during overflow periods is presented in Figures 91 - 95. These sequential sample plots illustrate unique loading profiles for each of the stations. The correlation between water quality parameters is most apparent for the Connecticut Street Regulator (Figure 91). The ammonia and nitrite-nitrate nitrogen, total phosphate, COD, settleable, volatile and suspended solids all peak after more than 10 hours while the BOD loading appears highest initially and gradually declines.

Sequential averaged data for Chelan Regulator (Figure 92) is characterized by two initial peaks within the first hour for ammonia, nitrite-nitrate nitrogen, total phosphate and BOD. Solids and COD, with delayed peaks, follow the trend of the Connecticut regulator.

Table 33. REGULATOR HISTORY AND CHARACTERISTICS

Station	Regulator Sampler		Date Started				Station History	Sampling Water Quality Stations		Comments
	Sequential	Composite	Water Quality	Over flow Volume	Matching Flow	Rainfall		Offshore	Nearshore	
Denny Local		Yes	4/70	11/70	4/71	3/70	Occasional recorder malfunctioning	189 1741	230-234	Good composite-Historical
Denny Lake Union	Yes		9/70	10/70	2/71	3/70	Some malfunctioning of sequential sampler and recorder	189 1741	230-234	Look at recent flow bact. with time
King		Yes	5/71	4/71	9/71	4/71	Few overflows	188-189 1741	235-234	Good composite - recent
Connecticut	Yes	Yes	6/71	4/71	6/71	4/71	Good sequential data	188, 184 1741,189	234, 235 236	Good sequential - recent
Lander		Yes	6/71	6/71	6/71	4/71	Few Overflows	188, 184 189,1741	301, 236 302, 303	
Hanford		Yes	5/71	4/71	6/71	4/71	Occasional malfunctioning of sequential sampler	184 188	301 236 302	
Chelan	Yes		9/70	/71	10/71	11/69	Seldon Overflows	188, 189 184	301, 304	
Harbor Avenue		Yes	11/69	3/70	3/71	11/69	Hill Steep, rapid runoff, frequent small overflow	181, 174 182, 183 184	238, 237	Good composite - historical and recent
Brandon		Yes	12/69	1/71	4/71	11/69		181, 174 182, 183 184	237	Good composite - historical and recent
Michigan	Yes		12/69	8/70	3/71	11/69	Frequent pump problems in sampler	181, 174 182, 183 184	237, 306	Good sequential - historical and recent
West Michigan		Yes	12/69	3/70	4/71	11/69	Hillside with many overflows	181, 174 182, 183 184	237, 305	
8th Avenue South		Yes	12/69	1/72	2/72	11/69	Very seldon overflows	182, 183 184	307	
Norfolk	Yes		12/69	—	—	11/69	No overflow data,	182, 183 184	307	

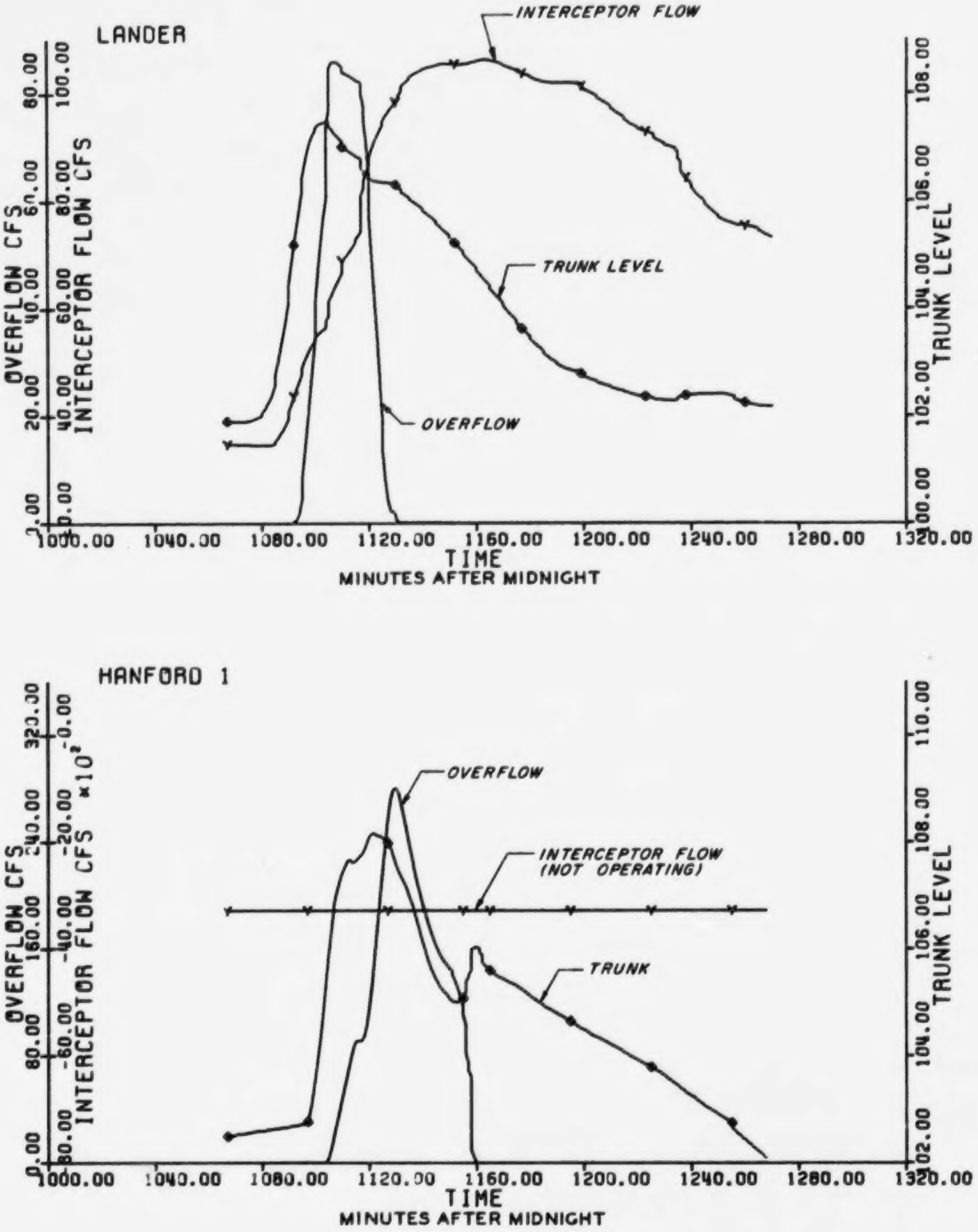


FIGURE 89

OVERFLOW CHARACTERISTICS OF LARGE STORAGE STATIONS

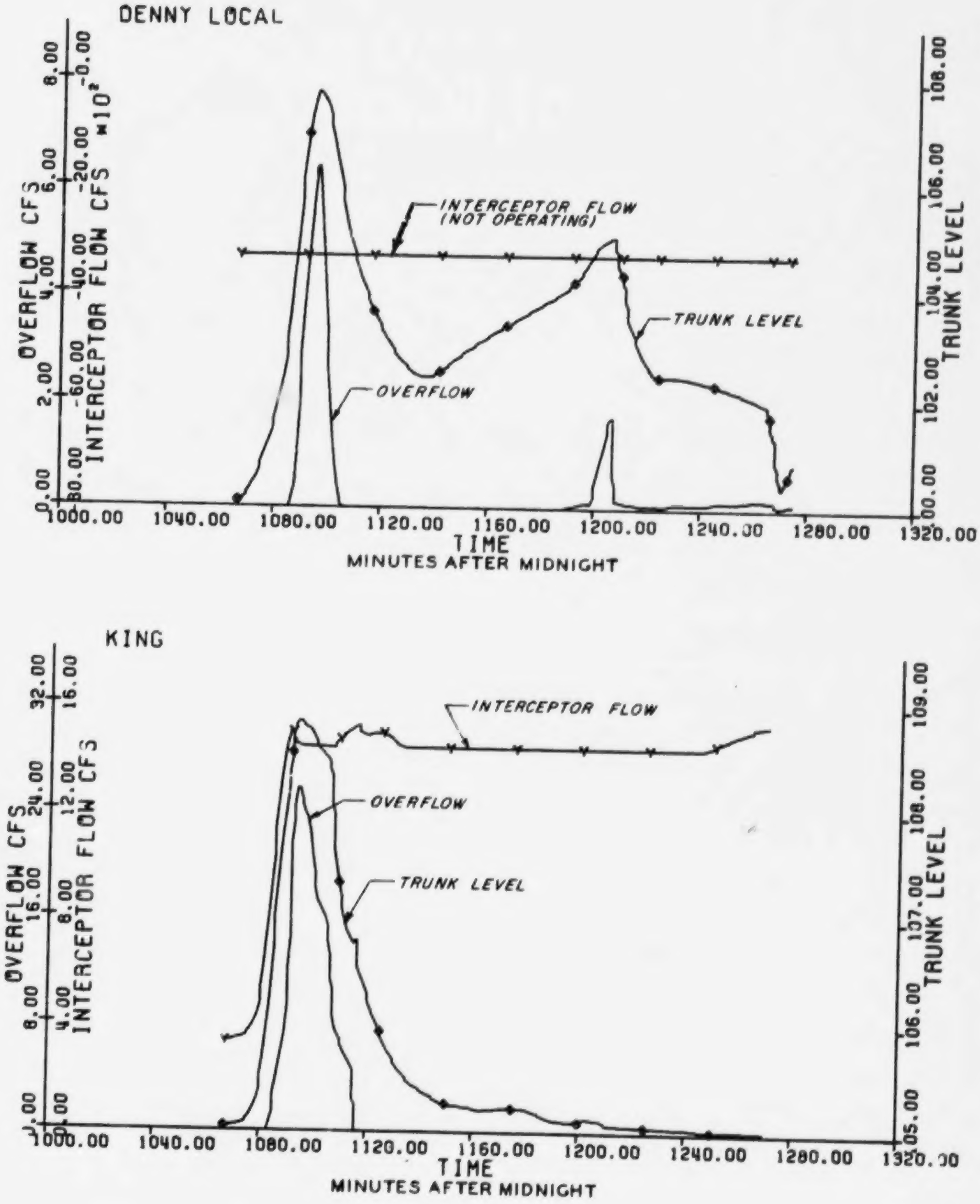


FIGURE 90

OVERFLOW CHARACTERISTICS OF SMALL STORAGE STATIONS

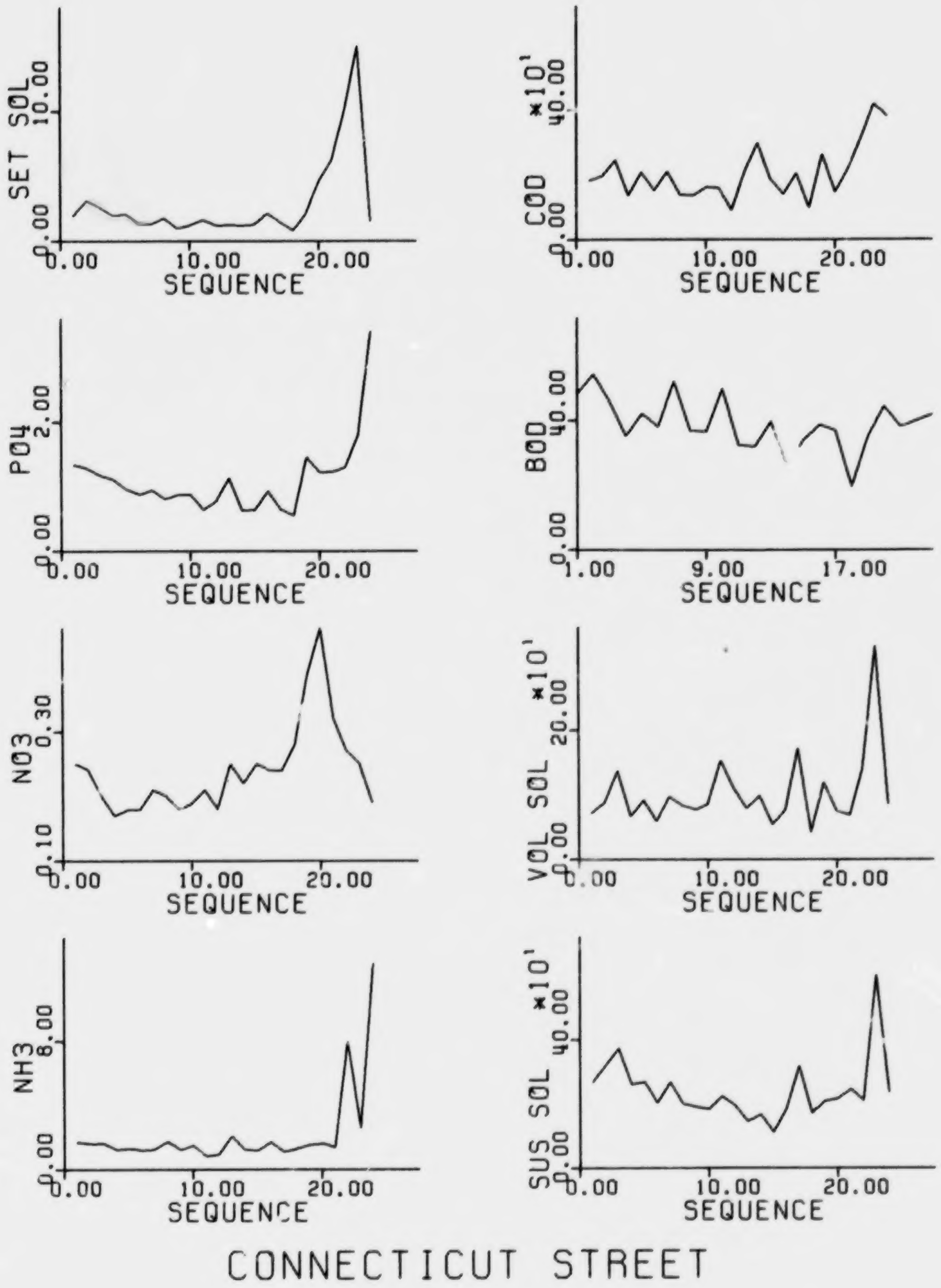


FIGURE 91

CONNECTICUT STREET OVERFLOW QUALITY VARIATION

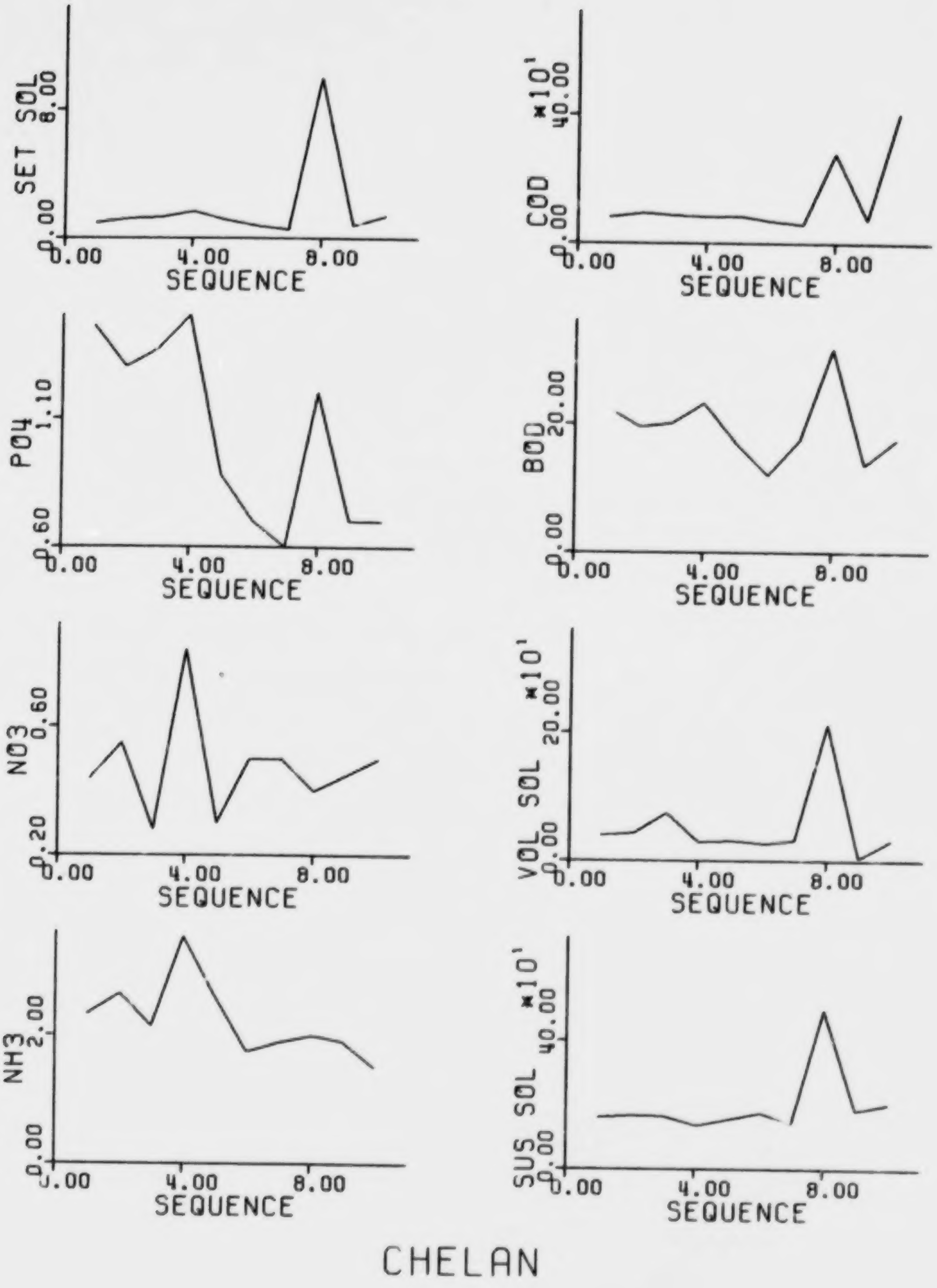


FIGURE 92

CHELAN OVERFLOW QUALITY VARIATION

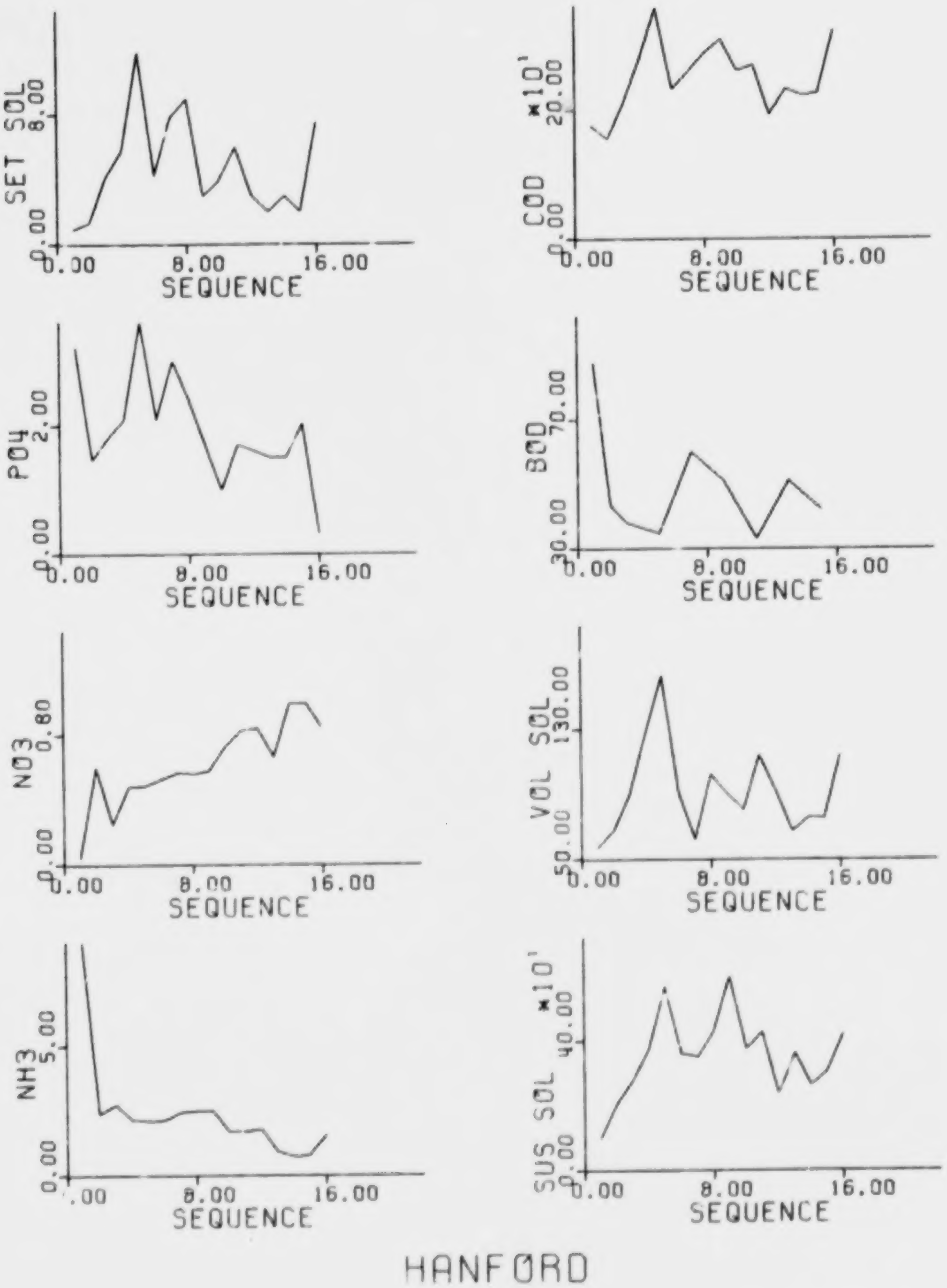


FIGURE 93

HANFORD OVERFLOW QUALITY VARIATION

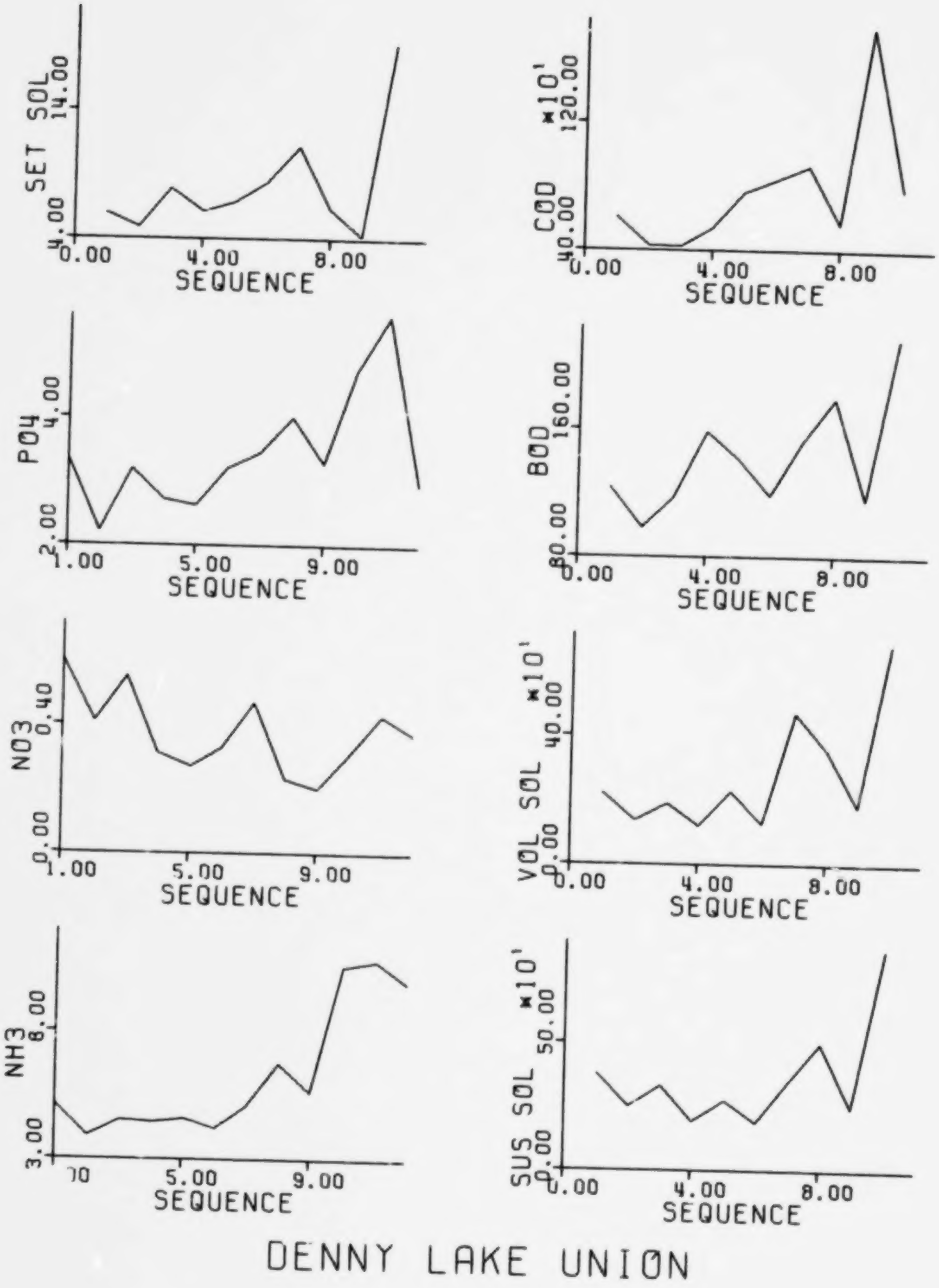


FIGURE 94

DENNY LAKE UNION OVERFLOW QUALITY VARIATION

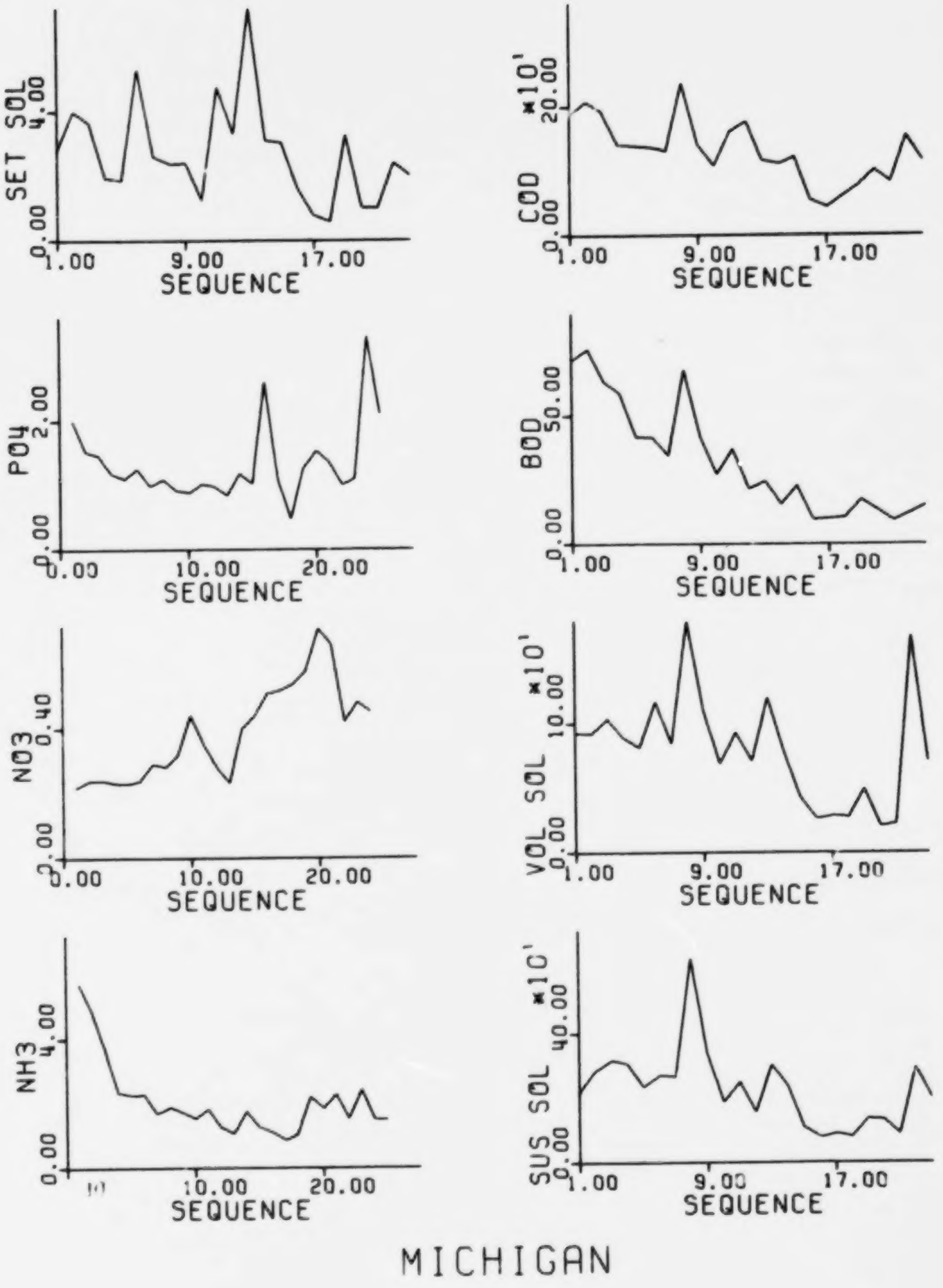


FIGURE 95

MICHIGAN OVERFLOW QUALITY VARIATION

The first flush effect appears to be represented best in Hanford Street regulator (Figure 93) for ammonia nitrogen, total phosphate, and BOD. Nitrite-nitrate nitrogen, solids and COD peaks lag by about one hour, with a steady increase of the nitrite-nitrate with time. The Denny Way-Lake Union Regulator (Figure 94) has ammonia-nitrogen, total phosphate, solids, BOD and COD with highest values toward the end of the sampling sequence similar to Connecticut Street.

At Michigan Street Regulator (Figure 95), the high initial peak occurs for ammonia nitrogen, BOD and to a lesser extent, for COD. The nitrite-nitrate nitrogen and total phosphate peak is near the end of the sequence while the solids have a major peak after 1.5 hours.

Comparing parameter profiles between stations, some generalizations can be made. Stations 14, 23 and 31 have similar sequential profiles for the solids and COD concentrations. Stations 23 and 36 have some similarities for BOD, PO_4 and nitrite-nitrate nitrogen, while Stations 26 and 36 have similar responses to ammonia nitrogen loading.

Sequential sampling data from the five regulators is typical of the large amount of information collected during this study (Appendix M). The "first flush effect" is not obvious from this data. The automatic samplers were programmed to begin operating as the outfall gate opened. Overflows generally occur well after a storm has begun and water levels throughout the collection system have built up to their limits. This means that, at most stations, the heavy concentration of solids and other materials has probably already been diverted to the interceptor before the overflow begins and sampling takes place. At a few stations, like Hanford, Norfolk and to a lesser extent, Michigan, the drainage basin is spread out so the first flush from some portion of the basin would frequently be seen during an overflow.

Factors which might play a role in influencing arrival time of peak concentrations include drainage system configuration (see Figure 96), pipe slope and size, degree of separation, distances traveled, and land use of the service area. When the average sequential sample plots for each water quality parameter are overlaid on one another (Figure 97), distinctly different three-dimensional profiles become apparent for each regulator station. Each profile is much like a station "fingerprint" which usually repeats itself for different storm types.

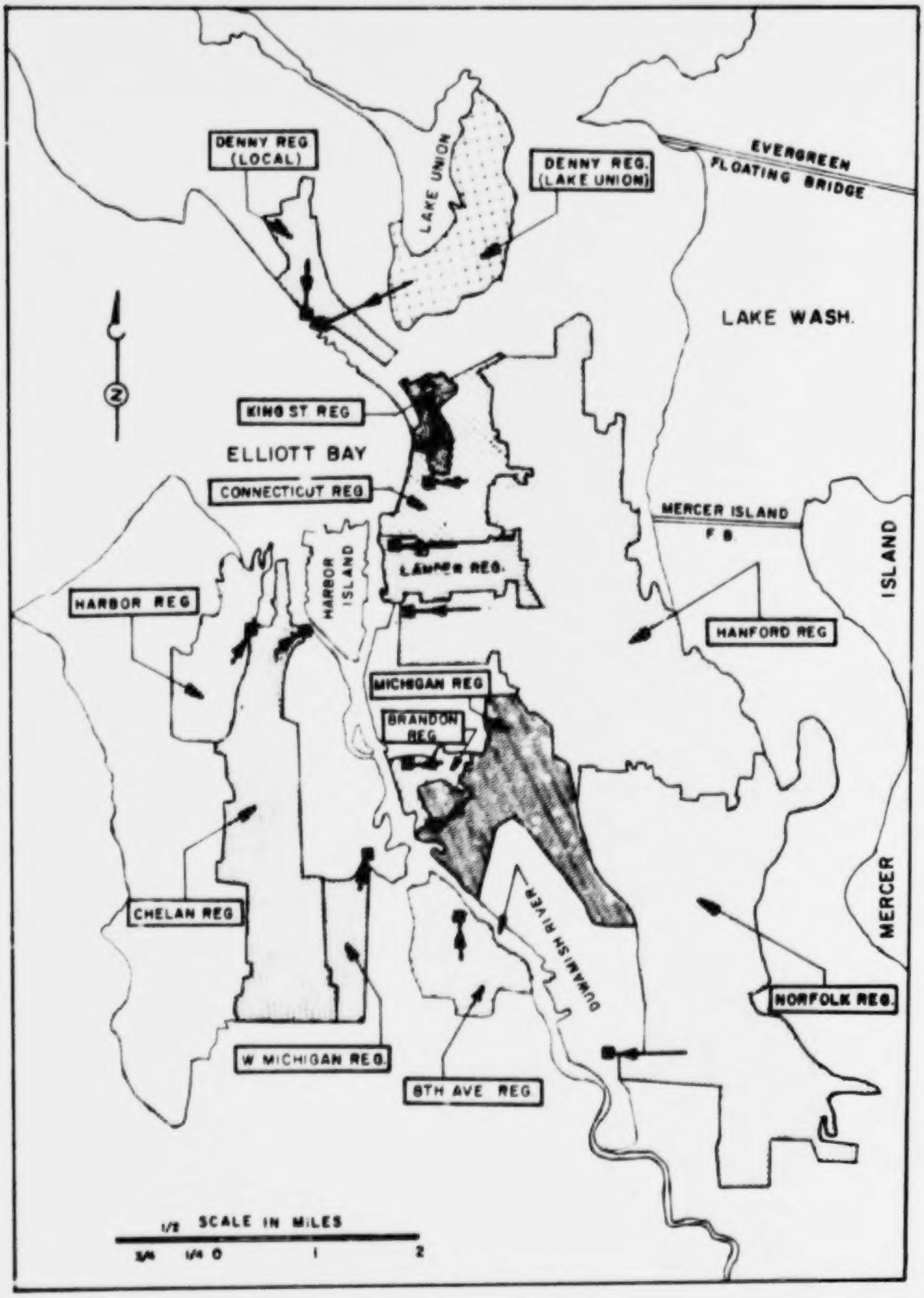

DENNY REG (LOCAL)
LAKE UNION
DENNY REG. (LAKE UNION)
EVERGREEN FLOATING BRIDGE
LAKE WASH.
N
KING ST REG
ELLIOTT BAY
CONNECTICUT REG
MERCER ISLAND F.B.
HARBOR ISLAND
LANDER REG.
HARBOR REG
HANFORD REG
ISLAND
MICHIGAN REG
BRANDON REG
DUWAMISH RIVER
MERCER
CHELAN REG
NORFOLK REG.
W MICHIGAN REG.
8TH AVE REG
SCALE IN MILES
1/2
3/4
1/4
0
1
2

FIGURE 96

REGULATOR DRAINAGE BASINS

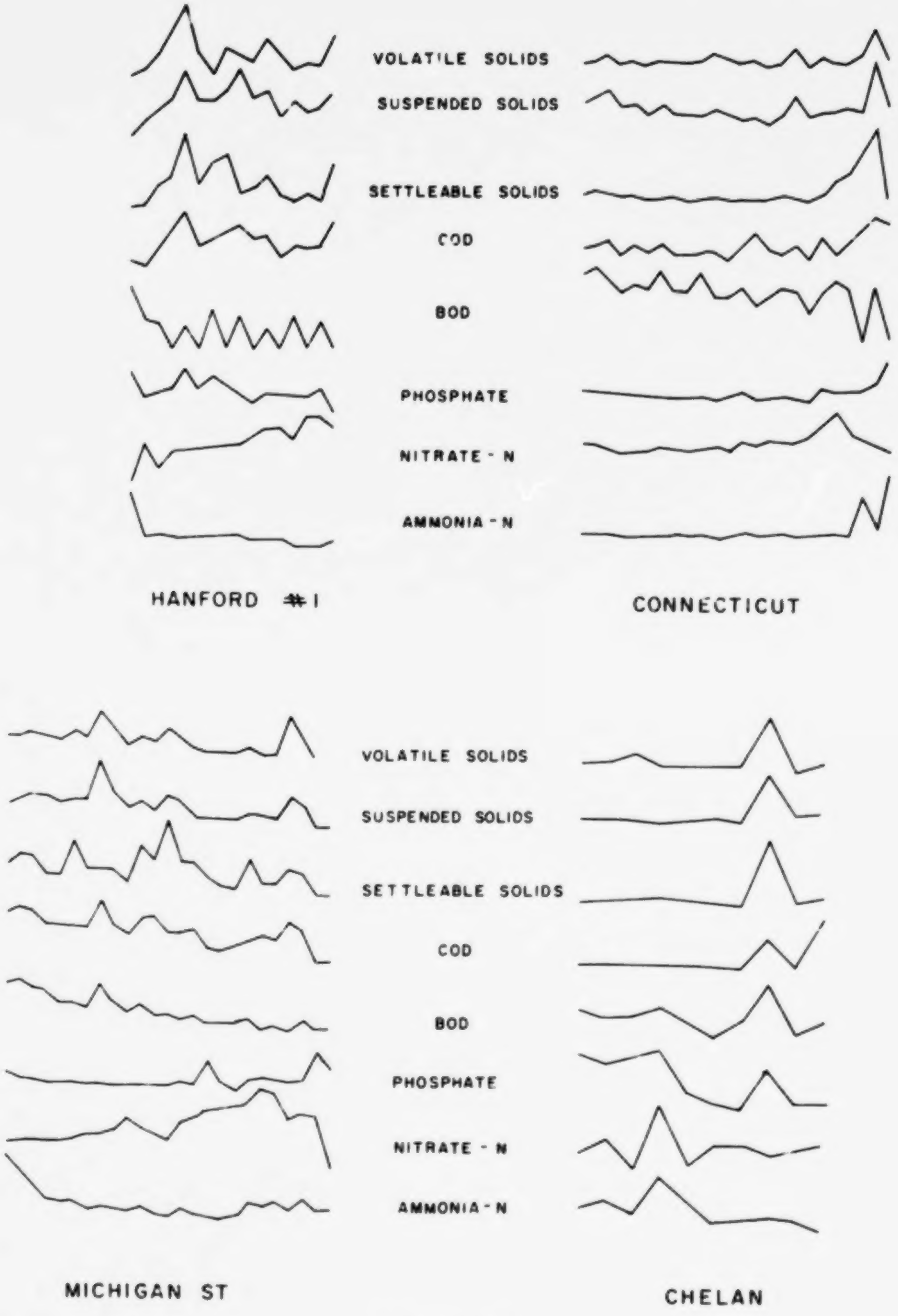


FIGURE 97

DISTINCT OVERFLOW PROFILES

Regulator water quality response to variations in rain intensity was anticipated but the variations in the response between regulators was quite dramatic. Table 34 shows maximum concentrations of various water quality parameters against average rain intensity. Eighth Avenue South regulator seldom overflowed so limited data is available. For those few overflows which did occur, all water quality parameters peaked during high average rain intensities (0.09 - 0.10 inch/hr). Most parameters at Harbor Avenue and Brandon Street peaked at relatively low rain intensities of 0.02 to 0.03 inch per hour. The storage capacity of Harbor Avenue and Brandon Street regulators are 0.6 to 5.14 hours and dry-weather flows, 0.02 to 0.3 million gallons, respectively (see Table 3). If Brandon Street is compared to Michigan Street, which has similar storage time but twice the storage capacity, peak values usually occurred at higher storm rates for solids but not for the nutrient parameters measured. The nutrient relationship cannot be entirely explained at this time. Both stations are served by a very long stagnant overflow line where septic waste would be unaffected by light rains. The lower solids peaks at both stations may be due to settling of materials and biological activity in the overflow lines.

The different response of each regulator to various rain intensities reaffirms that these stations are unique in their responses and impact on the environment. Present automatic control strategy is directed to minimze overflow volumes and, indirectly, loadings; but also considers receiving water capacities and standards. Future control strategies may need to consider the intensity and timing of peak overflow loading as a discharge limitation. If the objective is to minimize loading of a specific parameter, overflow priorities of individual stations should be assigned according to their optimum or lowest concentration response to rainfall intensity. If suspended solids were to be considered the critical parameter, then the sequence of overflowing might be as follows: Station 30, 34, 14, 13, 37, 31, 26, 25, 36, 23, 20 and 28 respectively. If BOD loading were the critical factor, the sequence would be: Station 36, 37, 13, 14, 30, 31, 20, 25, 26, 23 and 38.

Table 34. AVERAGE RAIN INTENSITY FOR PEAK WATER QUALITY PARAMETERS

Station	Suspended Solids (In. Rain-mg/l)	Settleable Solids (In. Rain-mg/l)	Volatile Solids (In. Rain-mg/l)	PO_4 (In. Rain-mg/l)	NO_3 (In. Rain-mg/l)	NH_3 (In. Rain-mg/l)	COD (In. Rain-mg/l)	BOD (In. Rain-mg/l)
Harbor	0.02 - 910	0.02 - 7.1	0.02 - 695	0.03 - 0.64	0.10 - 0.19	0.05 - 0.40	0.02 - 1400	0.02 - 1400
Brandon	0.03 - 590	0.03 - 2.6	0.03 - 320	0.03 - 0.97	0.04 - 0.05	0.06 - 0.45	0.03 - 480	0.03 - 145
Denny-Lk. Union	0.03 - 1000	0.04 - 15.0	0.03 - 590	0.03 - 0.92	0.04 - 0.14	0.05 - 1.45	0.04 - 5000	0.04 - 460
Denny-Elliott	0.05 - 610	0.03 - 16.0	0.03 - 690	0.02 - 0.52	0.05 - 0.07	0.03 - 0.69	0.03 - 1700	0.04 - 150
West Michigan	0.05 - 840	0.05 - 4.9	0.07 - 230	0.06 - 0.34	0.03 - 0.14	0.02 - 1.90	0.02 - 330	0.03 - 120
Chelan	0.06 - 158	0.06 - 2.2	0. 6 - 66	0.03 - 0.23	0.09 - 0.25	0.06 - 0.38	0.06 - 110	0.06 - 50
Hanford	0.06 - 410	0.06 - 9.0	0.06 - 190	0.10 - 0.64	0.06 - 0.02	0.04 - 1.48	0.06 - 400	0.07 - 250
Lander	0.07 - 540	0.07 - 3.0	0.07 - 425	0.12 - 0.21	0.12 - 0.06	0.03 - 0.34	0.07 - 1000	0.07 - 230
Michigan	0.07 - 490	0.08 - 1.4	0.08 - 330	0.03 - 0.24	0.03 - 0.07	0.03 - 0.85	0.04 - 1340	0.02 - 90
Connecticut	0.07 - 630	0.07 - 6.6	0.10 - 280	0.08 - 0.23	1.04 - 0.8	0.05 - 0.32	0.06 - 370	0.08 - 110
King	0.10 - 760	0.09 - 16.2	0.07 - 780	0.10 - 0.49	0.03 - 0.065	0.08 - 0.89	0.06 - 1400	0.06 - 285
Eighth South	0.10 - 680	0.10 - 6.0	0.10 - 111	0.09 - 0.19	0.12 - 0.08	0.09 - 0.31	0.09 - 85	0.10 - 14

System Overflow Loading to Receiving Waters

Difficulties were encountered in total loading calculation because of the previously reported variations in loading with time and rain intensity and because of some missing data resulting from sampling or recording equipment problems. Therefore, the total loading and probably loading reduction resulting from CATAD operation must be assessed from a total summation of available data on each parameter. By treating the extreme values generated before CATAD was fully operational as conservative estimates of loading without control, then differences noted in the remaining 80-90 percent of the data should reflect reduced loading with control.

This approach to assessing nitrite-nitrate nitrogen loading in Figure 98 shows the initial large increases appearing by 0.2 inch of rain and then the rapid decline with dilution around 0.82 inch. At the extreme of 2.72 inches of rain, a slight increase with both controlled and uncontrolled loads coincides as the system approaches its hydraulic limits and surface runoff is at its maximum flushing capability. The apparent reduction in peak nitrite-nitrate nitrogen loading is 78 percent with CATAD control. Figure 99 shows a probable reduction of 84 percent in peak loading of ammonia-nitrogen with CATAD control. Figure 100 shows an apparent reduction of at least an 81 percent in peak phosphate load. The background COD data fits a well defined curve which is 88 percent higher than the CATAD controlled data in Figure 101. Normalized loading values for the suspended, settleable and volatile solids are combined in Figure 102. The apparent peak solids load reduction is around 85 percent. If the total loading, as reflected by the area under the curve, is computed, reduction in COD loading between 0.01 and 2.72 inches of rainfall is 80 percent. In the case of nitrite-nitrate nitrogen, loading reduction for the same range of rainfall would be 70 percent based on the area under each curve in Figure 99.

Combining the peak loading data from all stations into Table 35 shifts the total system reaction to control strategies and the peak loads to a higher intensity of rainfall. Thus it takes larger storms occurring at a less frequent time interval to produce a similar loading peak; another encouraging indicator of CATAD performance. The next pages of this section will examine total system reaction to storms concluding with an evaluation of system performance.

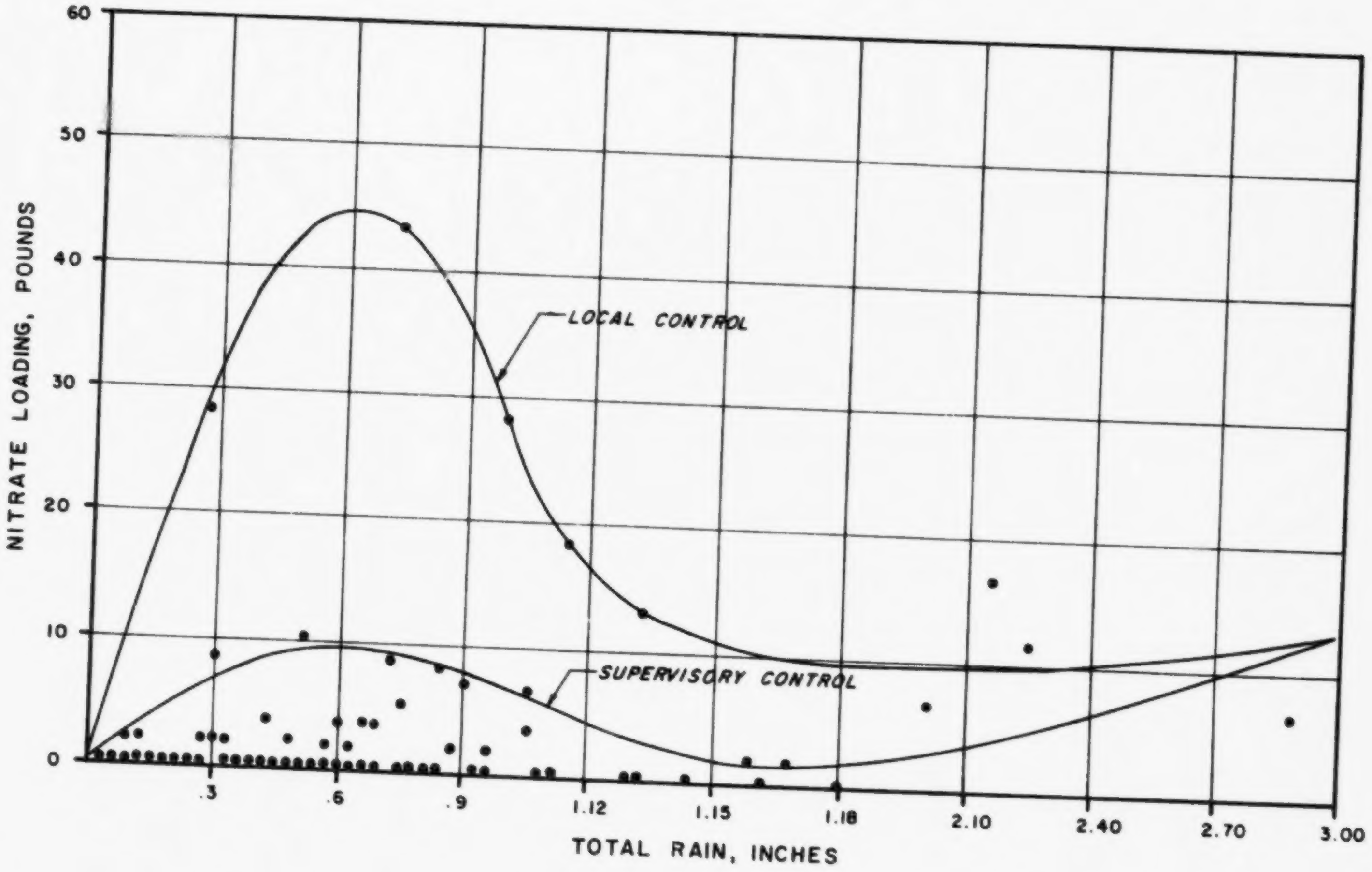


FIGURE 98

NITRATE, COMPARATIVE PEAK LOADINGS

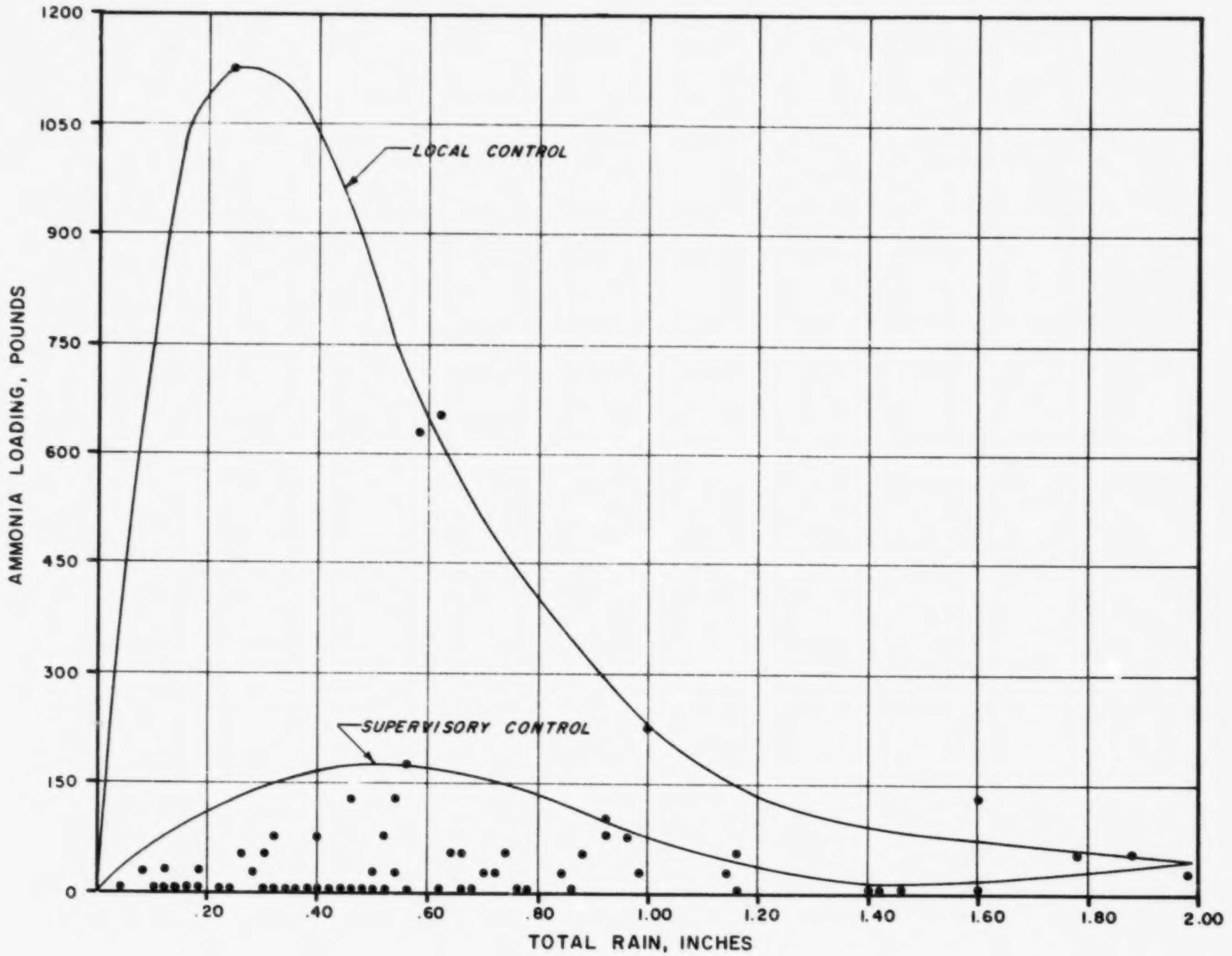


FIGURE 99

AMMONIA, COMPARATIVE PEAK LOADINGS

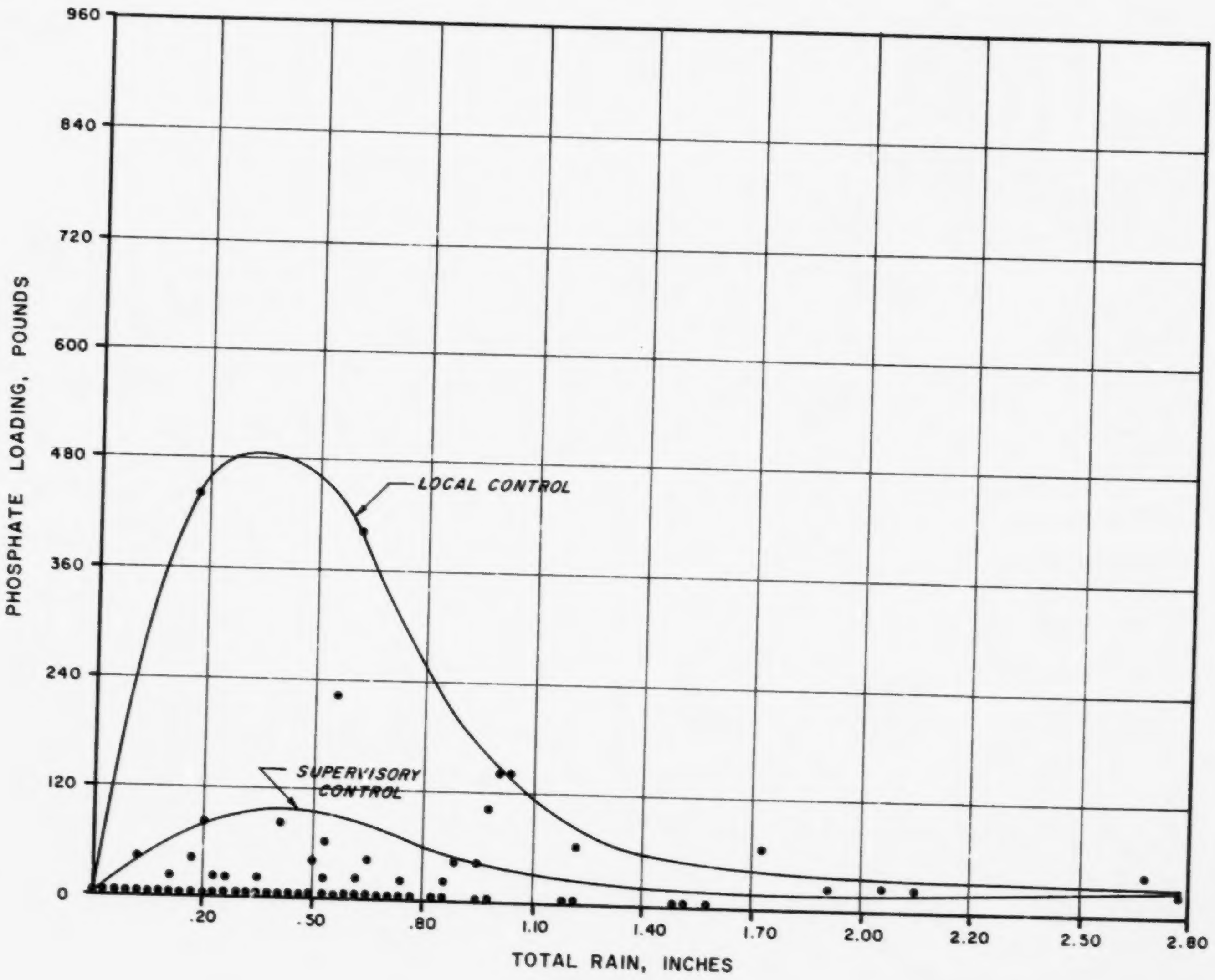


FIGURE 100

PHOSPHATE, COMPARATIVE PEAK LOADINGS

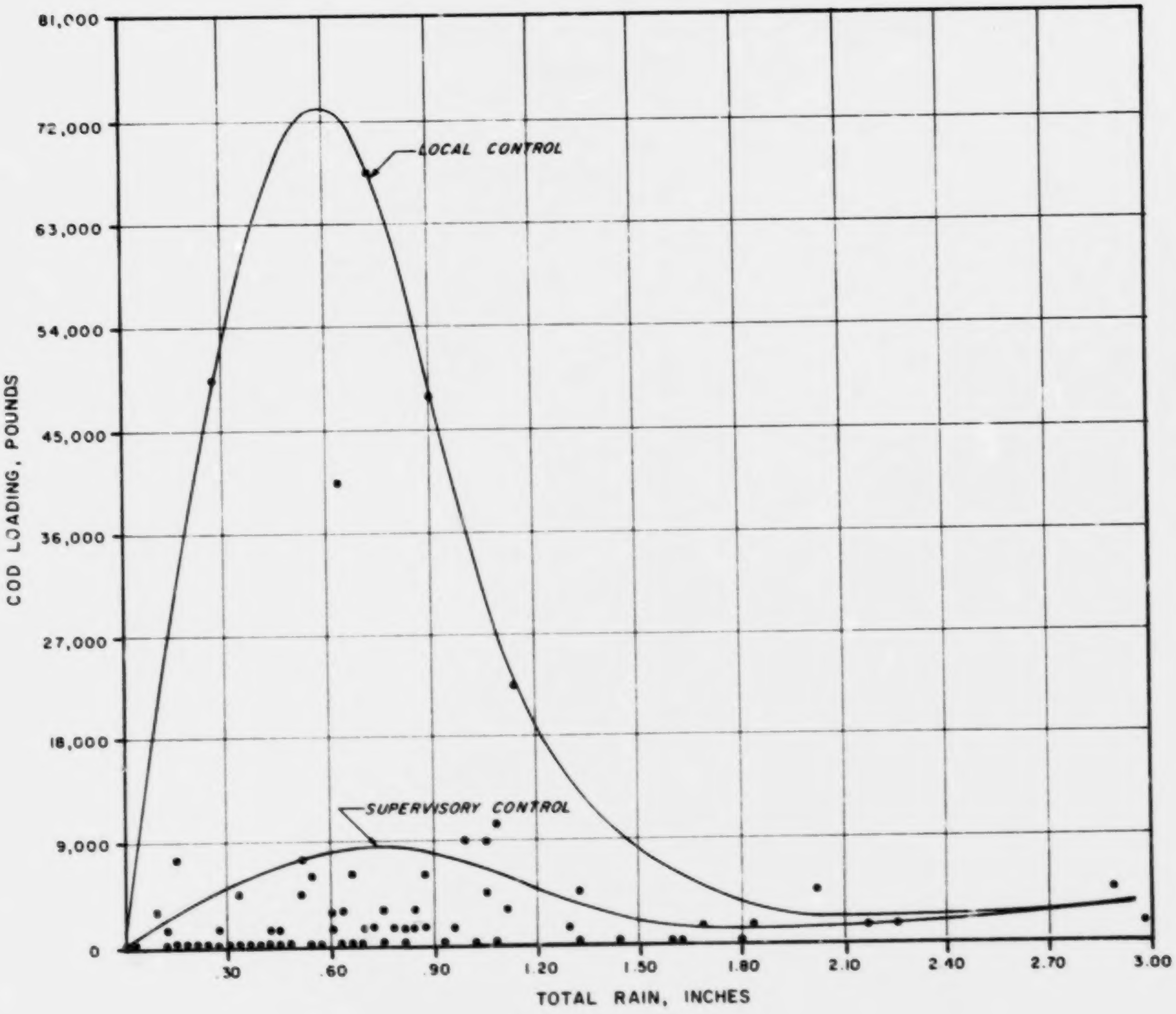


FIGURE 101

CHEMICAL OXYGEN DEMAND, COMPARATIVE PEAK LOADINGS

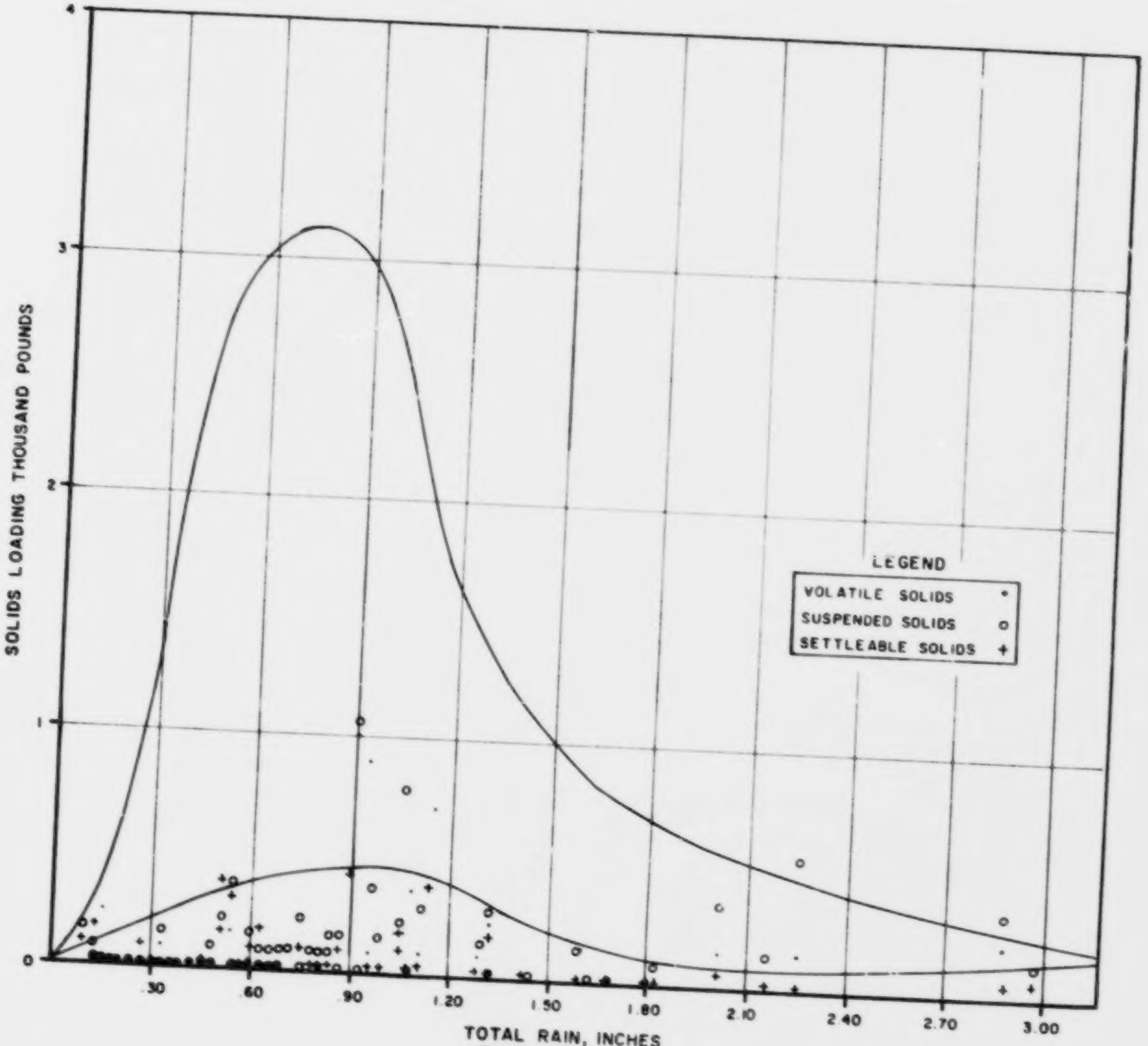


FIGURE 102

SOLIDS, COMPARATIVE PEAK LOADING

Table 35. TOTAL RAIN IN INCHES FOR ESTIMATED PEAK LOADING ALL STATIONS

BEFORE CATAD CONTROL		AFTER CATAD CONTROL
NH_3 -	0.30	0.60
NO_3 -	0.55	0.60
COD -	0.50	0.65
PO_4 -	0.45	0.50
Combined Solid Analysis	0.60	0.85
Average:	0.48	0.64

OVERFLOW ANALYSES

The Data

The most direct evaluation of the effectiveness of the "total systems management" concept as applied to combined sewer control facilities such as CATAD, is system-wide comparison of overflow and rainfall data through the various control phases. The overflow data includes volume, number of overflows for the system during any storm, and the number of storms during which overflows occurred. Rainfall data includes total rainfall in inches per storm, maximum rainfall intensity in inches per hour, average rainfall intensity and storm type.

Computer programs condensed the data from separate overflow and rain gaging stations as discussed earlier in this section. The condensed data was merged into individual records for each storm, then analyzed by a table-generating program described later in this section. Computer plots presented these comparisons. Data volume and the number of different analyses desired suggested this form of automated data processing using the same computer which monitors and controls the sewage collection system. A total of 514 storm events was recorded during the three and one-half year demonstration grant period. In 341 of these storm events, a total of 762 separate overflows was recorded. The average of 2.23 overflows per storm is considered low because of the five to ten percent data loss caused by mechanical failures of recording and sampling equipment. However, more than 60 percent of the recorded storms resulted in only one overflow, or no overflows at all; so the average is greatly influenced by multiple overflows during a few heavy storms.

The drainage study areas shown in Figure 96 and itemized in Appendix A total approximately 13,000 acres. Overflow and loading data for those overflows where nearly all data was available are listed in Appendix L.

Overflow Volumes

Figure 103 is a computer plot of every overflow event during the grant study except for the 5 percent of storms which fall outside the range of the axis of the graph and for those small overflows during storms under 0.05 inch of rainfall. The obvious scatter effect indicates the difficulty in correlating system overflows because of the many variables which influence the nature of the storm and station reaction. The computer generated regression line evaluates every overflow, whether it is plotted on the graph or not; so the line represents the best estimate of overflow expected from the entire system for any given rainfall. Note that the vast majority of overflows above the regression line occurred during the local control period.

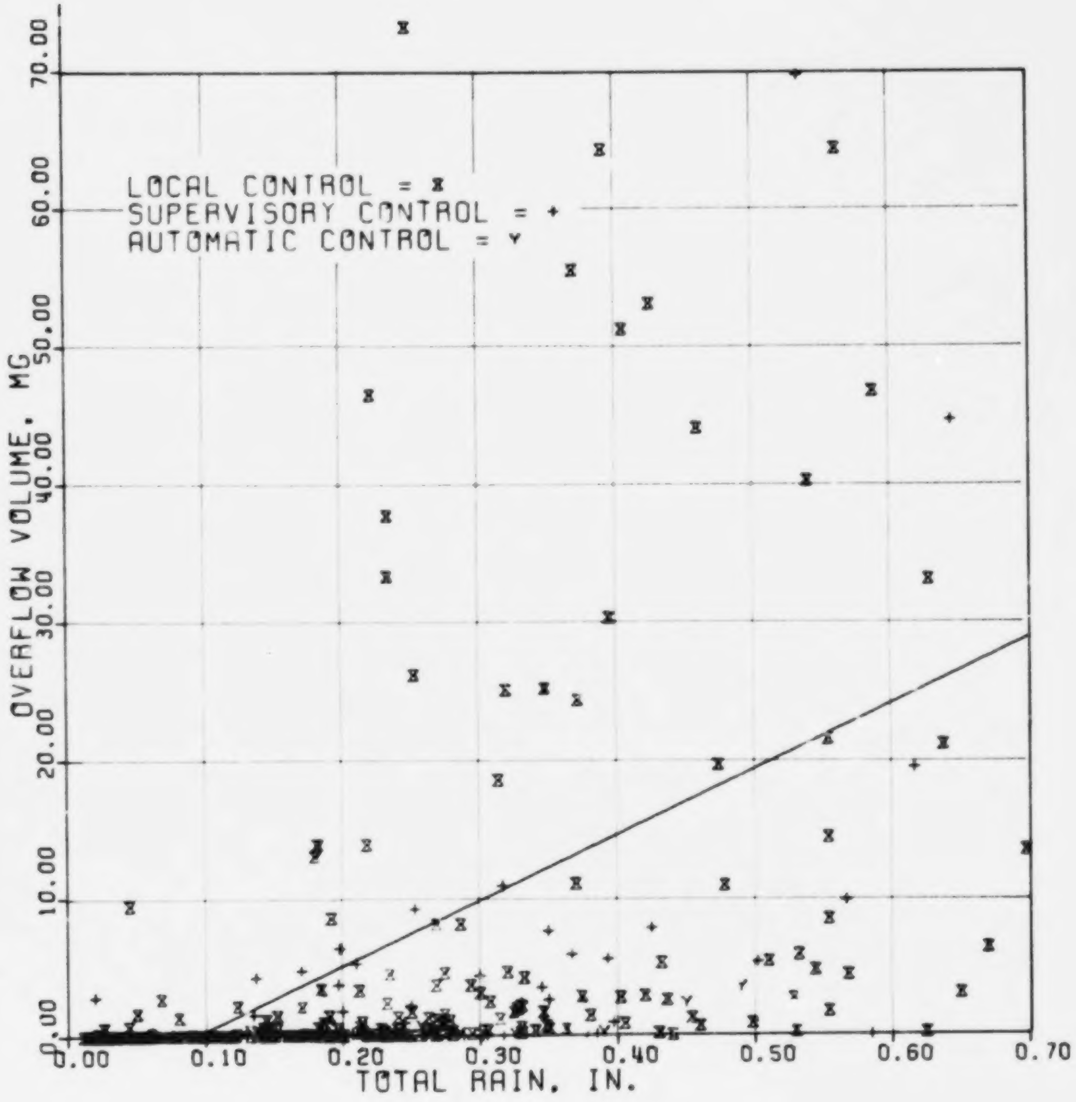


FIGURE 103

OVERFLOWS DURING ALL CONTROL PHASES COMBINED

Figure 104 shows similar computer regression lines drawn through overflow events occurring for each of the three control modes. The vertical axis changes on each plot providing early indication of the reduced system overflow volume for advanced control techniques. The individual plots of Figure 104 are merged onto Figure 105 for comparisons of each mode on the same vertical scale. In addition to the three control modes previously plotted and combined on this figure, an additional line has been added to show the improvement of local control, meaning mechanically driven gate regulators, compared to "uncontrolled" static-type regulators which have side spill weirs or orifice plate devices. Information from this figure is used to project overflow amounts and cost savings which may be expected by cities implementing one or more of these control phases. Other agencies considering some form or combination of these control modes can use this figure to anticipate overflow volume from similar drainage areas and storm volumes.

Indication of total system performance is obtained from Figure 105 by drawing a vertical line at a chosen rainfall amount and comparing the overflow volume indicated by the regression lines. For example, at 0.30 inch total rainfall, the estimated overflow volumes from Figure 105 are shown on Table 36 together with a percentage of reduction over less complex control modes.

Table 36. ESTIMATED OVERFLOWS AND REDUCTIONS FOR A SYSTEM

Control Mode	Overflow, MG[a]	Percent Overflow Reduction	
		vs. "Local"	vs. "Static"
Static Regulator	15.38	----	----
Local Control	8.98	----	41.6
Supervisory Control	4.91	43.3	68.1
Automatic Control	.49	94.5	96.8

---

[a] From Figure 105 at 0.30 in. rain.

These performance estimates should be considered with some degree of caution when comparing results among cities because of different operating bases upon which overflow reduction calculations are made. Automatic control reductions above 90 percent are based on limited data for the summer period of 1973. These values should not be considered firm, but rather an indication of excellent system reaction to the unusually light rainfalls experienced in the Seattle area for the early part of 1973. The 60 percent overflow reduction during the supervisory control period is an expectable lower limit, and a final performance level will probably fall somewhere between

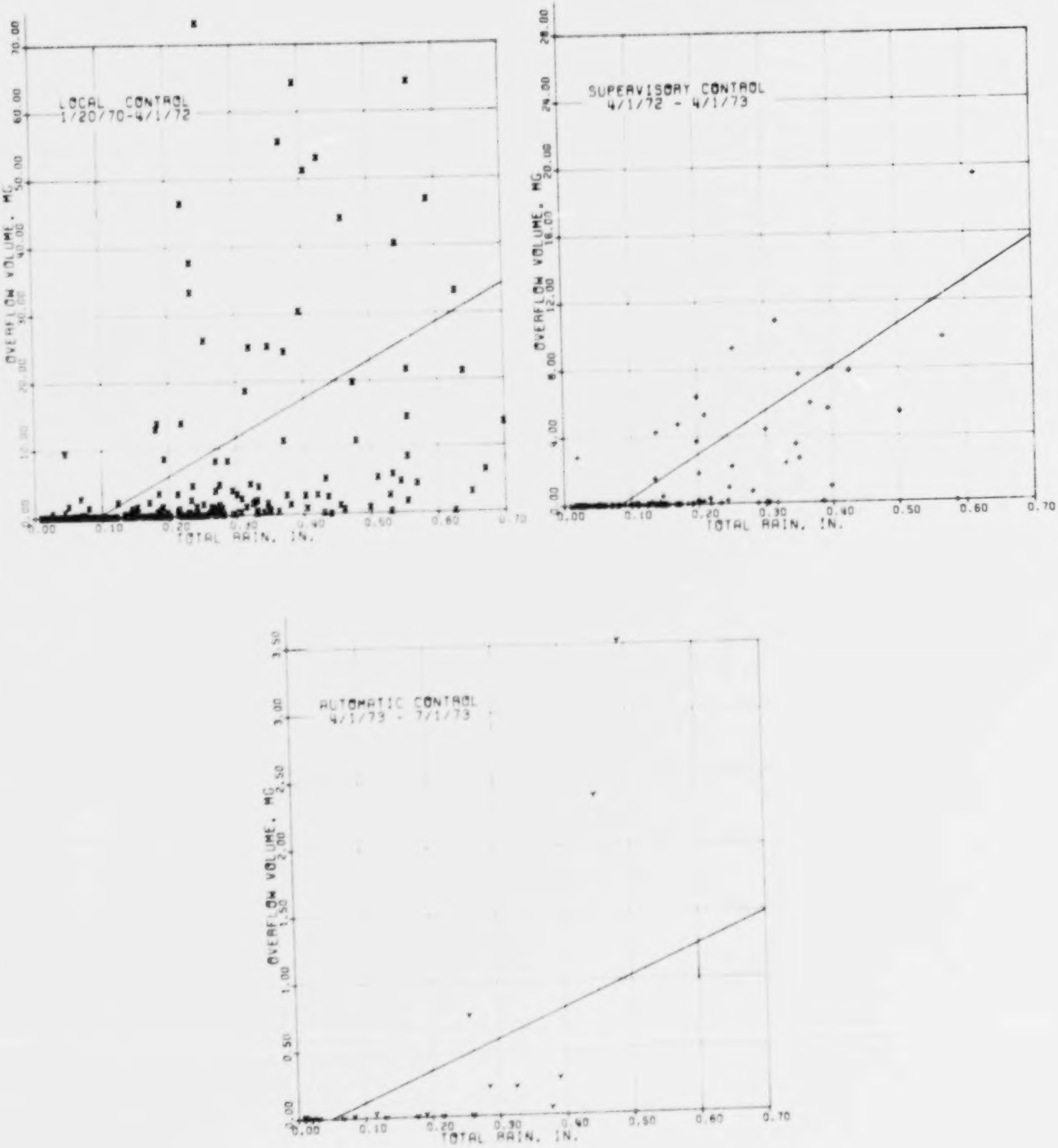


FIGURE 104

OVERFLOWS FOR EACH CONTROL MODE

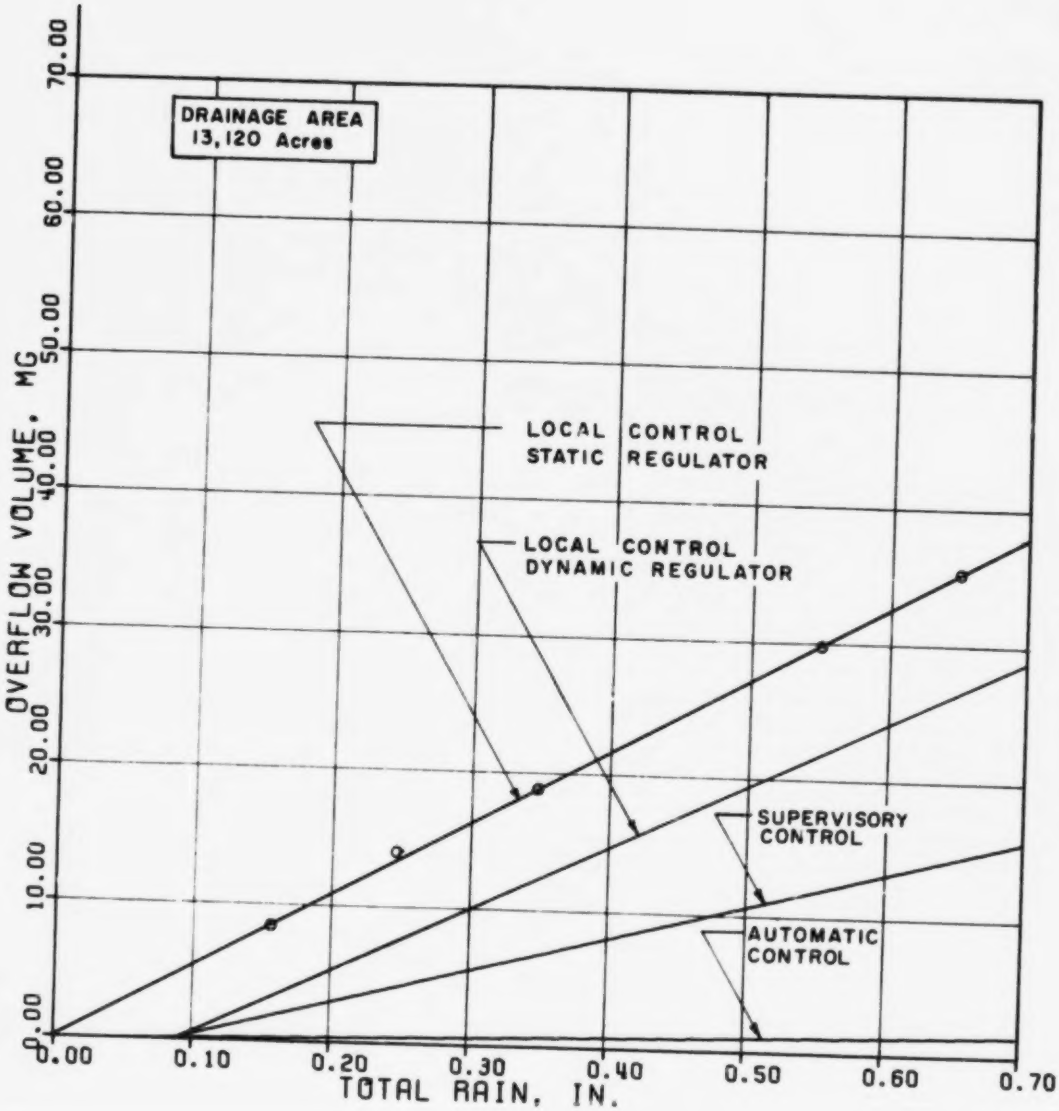


FIGURE 105

REGRESSION LINES FOR EACH CONTROL MODE

these two extremes as more rainfall data is gathered and additional routines are added to the automatic control program.

Tabular Overflow Analyses

Standard statistical analyses merely repeated the obvious conclusion that there is no good correlation between overflow volumes and measured storm characteristics; therefore, a program was written to segment the data into storm ranges and analyze average overflows for each of these storm periods. Storm volumes and the number of overflows during storms were analyzed in this manner, and the program was made flexible enough to not only segment the data into ranges of total rain, maximum intensity or average intensity, but also to separate the data according to its control mode, storm pattern, or time period. A sample output table from this program is included as Table M-1 in Appendix M. Percent overflow reductions are computed for the different control modes versus local control for each selected storm range; then summarized as an overall percent reduction or a weighted percent reduction. Weighting is performed by multiplying the percent reduction for a given range by the number of storm events measured and averaged for the higher level control mode.

Table 37 shows how the program reacts in computing percent reductions by varying the rainfall range over which the computations are made. Note the influence of the weighting factors. In most cases, the weighting slightly improves the percentage reduction because the greater number of observations are usually in the lower rainfall ranges where percent reductions are slightly better. This is not universally true as demonstrated by the storm interval of 0.05 inch where, under combined automatic and supervisory control, weighting decreases the performance from a minus 1.3 to a minus 48.4 percent reduction. The final column in Table 37 summarizes the percent reductions calculated under all rainfall ranges. Since the range beginning at 0.1 inch is quite close to that summary, this total rainfall range was selected for comparisons made in this section.

A negative percent reduction is equivalent to reporting a percent increase. These increases are nearly all in the "number of overflows" column, reflecting the gate control performed during the advanced control modes. By selectively overflowing and shaving off certain peak overflows at many regulators, the system significantly decreases overflow volume to the receiving water. The former local control procedure allowed a particular regulator gate to remain open for a long period of time, recording only one overflow. However, that overflow was very large in volume.

Table 37. PROGRAM ANALYSIS OF PERFORMANCE AT DIFFERENT STORM RANGES

Average Range		Percent Overflow Reduction								
		Supervisory vs. Local			Automatic vs. Local			Auto. + Supervisory		
		Overall	NM[a]	Weighted	Overall	NM[a]	Weighted	Overall	NM[a]	Weighted
0.05	Overflow Volume	26.0	11	37.5	94.6	8	96.6	61.0	11	68.8
	Number Overflows	-41.1		-57.0	15.3		16.8	- 1.3		-48.4
0.10	Overflow Volume	34.8	9	50.8	94.7	6	97.0	65.6	9	77.6
	Number Overflows	-35.1		-20.2	16.3		38.7	4.6		6.0
0.25	Overflow Volume	13.5	5	67.7	96.1	3	97.3	55.6	5	84.3
	Number Overflows	-30.4		-27.2	21.4		54.4	11.2		14.3
0.5	Overflow Volume	17.0	3	68.4	94.3	2	92.2	56.6	3	82.9
	Number Overflows	-31.2		-10.5	3.9		20.2	2.3		6.1
1.0	Overflow Volume	54.9	2	54.4	95.5	1	---	76.3	2	74.9
	Number Overflows	-44.5		-11.2	36.5		---	11.9		13.1
2.0	Overflow Volume	59.3	1	---	96.6	1	---	78.0	1	---
	Number Overflows	-11.0		---	39.0		---	14.0		
Summary	Overflow Volume	34.3		55.8	95.3		95.8	65.5		77.7
	Number Overflows	-32.2		-25.2	22.1		32.5	7.1		- 1.8

[a] NM represents number of rainfall ranges where each control mode had at least one storm to compare.

Total system summer performance is compared with annual performance in Table 38. In this table, the effect of limited data becomes quite apparent. Intense, short duration storms on two occasions during the automatic and supervisory control periods were compared with a single long duration storm during the local control period. This single comparison had a very negative effect on the overall summertime performance. Since the annual performance is considerably higher, supervisory and automatic control appear most effective in reducing overflows during the winter rainy season when local control proved ineffective in minimizing total system overflows. The evidence of some improvement in receiving water conditions during summer months does indicate some question remains regarding the limited summer overflow data. Further summer data and comparisons are required to evaluate total system summer performance.

The relationship between storm patterns and system performance for various control modes was analyzed. The results are presented in Table 39. The best automatic control performance was during the localized type of storm, as expected. The least effective performance was for uniform area-wide storms where fewer alternative control actions are possible. However, supervisory control was more effective for uniform storms by reducing the large number of local control overflows during this, the most common storm type recorded during the grant period.

Analyzing total rainfall alone ignores the fact rainfall duration plays an important role in total system reaction to a storm. Table 40 indicates how the system reacts to various storm characteristics. Lower overall performance for maximum rate is discounted because maximum rain may fall for very long or short durations. Therefore, maximum rainfall rates are not expected to truly represent actual performance. The average rainfall rate considers not only total rainfall, but also the duration over which the rain fell. As shown by the table, both supervisory and automatic control performance for average rainfall rates have been outstanding when compared to local control. Since earlier reports have relied upon total rainfall as the performance criteria, this method is used later in this section to measure CATAD total system performance for various control modes.

System Overflow Loading Analyses

The tabular analysis program was next applied to the eight different loading parameters recorded during the course of the grant study. Loading percentage reductions are presented in Table 41. Because of the limited amount of loading data available for the automatic control mode, supervisory and automatic control periods were combined and considered as advanced control measures. The overall loading reductions for advance control vary from 57.7 percent reduction in ammonia loading to 75.7 percent reduction in COD loading;

Table 38. SYSTEM PERFORMANCE FOR SUMMER PERIODS

Time Period		Supervisory vs. Local		Automatic vs. Local		Auto + Supervisory	
		Overall	Weighted	Overall	Weighted	Overall	Weighted
All Year	Overflow Volume	34.8	58.1	+ 94.7	97.0	65.6	77.6
	Number Overflows	-35.1	-26.6	16.3	38.7	4.6	6.0
Summer (June - August)	Overflow Volume	-21.0	- 7.4	39.9	---	-13.4	-25.6
	Number Overflows	-20.8	- 9.7	62.5	---	53.5	51.7
Rain less than 2 in. average (May-September)	Overflow Volume	-100.2	-22.5	-26.9	26.0	-29.2	14.6
	Number Overflows	-54.1	-20.6	-66.9	- 4.4	-10.8	12.1

Table 39. SYSTEM PERFORMANCE FOR DIFFERENT STORM PATTERNS

Storm Pattern		Supervisory vs. Local		Automatic vs. Local		Auto + Supervisory	
		Overall	Weighted	Overall	Weighted	Overall	Weighted
All Types Combined	Overflow Volume	34.8	58.1	94.7	97.0	65.6	77.6
	Number Overflows	-35.1	-26.6	16.3	38.7	4.6	6.0
Uniform Area-Wide	Overflow Volume	33.6	31.0	86.5	83.4	65.3	57.2
	Number Overflows	-31.7	-68.1	-62.5	-70.3	16.1	-69.2
Frontal or Traveling	Overflow Volume	-59.	-66.3	95.9	95.3	19.5	14.9
	Number Overflows	-59.	-44.9	- 8.7	-24.2	- 6.7	-24.2
Pocket or Localized	Overflow Volume	12.4	0.9	97.2	97.2	55.7	49.5
	Number Overflows	-20.4	-31.8	27.3	27.3	27.4	9.8

Table 40. SYSTEM PERFORMANCE FOR DIFFERENT STORM CHARACTERISTICS

Storm Characteristics	How Analyzed				PERCENT REDUCTION					
	Low Limit	High Limit	Average Interval		Supervisory vs. Local		Automatic vs. Local		Automatic & Local Combined	
					Overall	Weighted	Overall	Weighted	Overall	Weighted
Total Rainfall Inches	0.01	2.00	.16	Overflow Volume	34.8	50.8	94.7	97.0	65.6	77.6
				Number Overflow	-35.1	-20.2	16.3	38.7	4.6	6.0
Maximum Rate In./Hour	0.01	0.25	.20	Overflow Volume	- 5.7	-30.7	96.4	96.1	46.0	75.4
				Number Overflow	- 0.5	2.4	31.6	19.1	29.2	23.4
Average Rate In./Hour	0.01	0.12	.01	Overflow Volume	73.6	81.9	97.0	97.2	85.8	91.1
				Number Overflow	2.0	10.6	37.3	49.9	29.1	33.0

Table 41. REDUCTION IN LOADING PARAMETERS

Loading Parameter	Percent Loading Reduction					
	Supervisory vs. Local		Automatic vs. Local		Super. & Auto.	
	Overall	Weighted	Overall	Weighted	Overall	Weighted
NH_3-N	15.5	0.0	----	----	57.7	50.0
NO_3 N	59.6	38.2	----	----	79.8	69.1
PO_4	35.8	25.8	----	----	67.9	62.9
Settleable Solids	39.0	10.0	63.4	63.4	65.9	51.7
Suspended Solids	36.5	9.7	67.6	67.6	65.0	52.0
Volatile Solids	42.0	23.2	72.9	72.9	68.3	59.2
BOD	28.8	28.3	----	----	64.4	64.2
COD	55.5	42.6	78.5	78.5	75.7	69.4
Average of All Loadings	39.1	22.2	70.6	70.6	68.0	59.8

for an overall average of 68.1 percent for all loading parameters. The reasons for the different reduction percentages are unclear, but may be due to the overflow volume reducing performance of individual regulators having high concentrations of particular parameters.

The loading data has a scattered effect much like the volume data plotted in Figure 103. Loading trends, however, became more obvious after applying a moving-average technique and plotting the data with the computer driven digital plotter. Figures 106 and 107 show loading trends for the different parameters as related to increasing total rainfall. The moving average technique clips off peaks and shifts the data location so that these figures should not be used to indicate any actual overflow data point, but rather to indicate trends. Under local control, there appears to be a lag in the buildup of loading discharged to the receiving water as rainfall volume increases until approximately 0.2 inch of rainfall. Then the buildup becomes steady and reaches a peak at about 0.5 inch. After the 0.5 inch peak is reached, some cases show a decline, but others do not show an obvious trend.

These figures can be interpreted to mean that a low rainfall intensity the pollutants analyzed are not appreciably dislodged from their source. Increasing rains then loosen these materials and transport them through the system to interception and overflow points until, for a storm in excess of 0.5 inch, there is a washed-out effect, when very little more material can be washed from the storm drainage system into the more constant pollutant quantities in the sanitary sewer sources of the combined sewer system. Table 42 compares the average peaks on these moving-average diagrams to give another indication of the improvement with advanced controls. Percent reductions were not calculated because the tabular data is considered more indicative of performance. However, Table 42 eliminates confusion caused by the differences in vertical scale (Figures 106, 107) which the computer plotter automatically assigns.

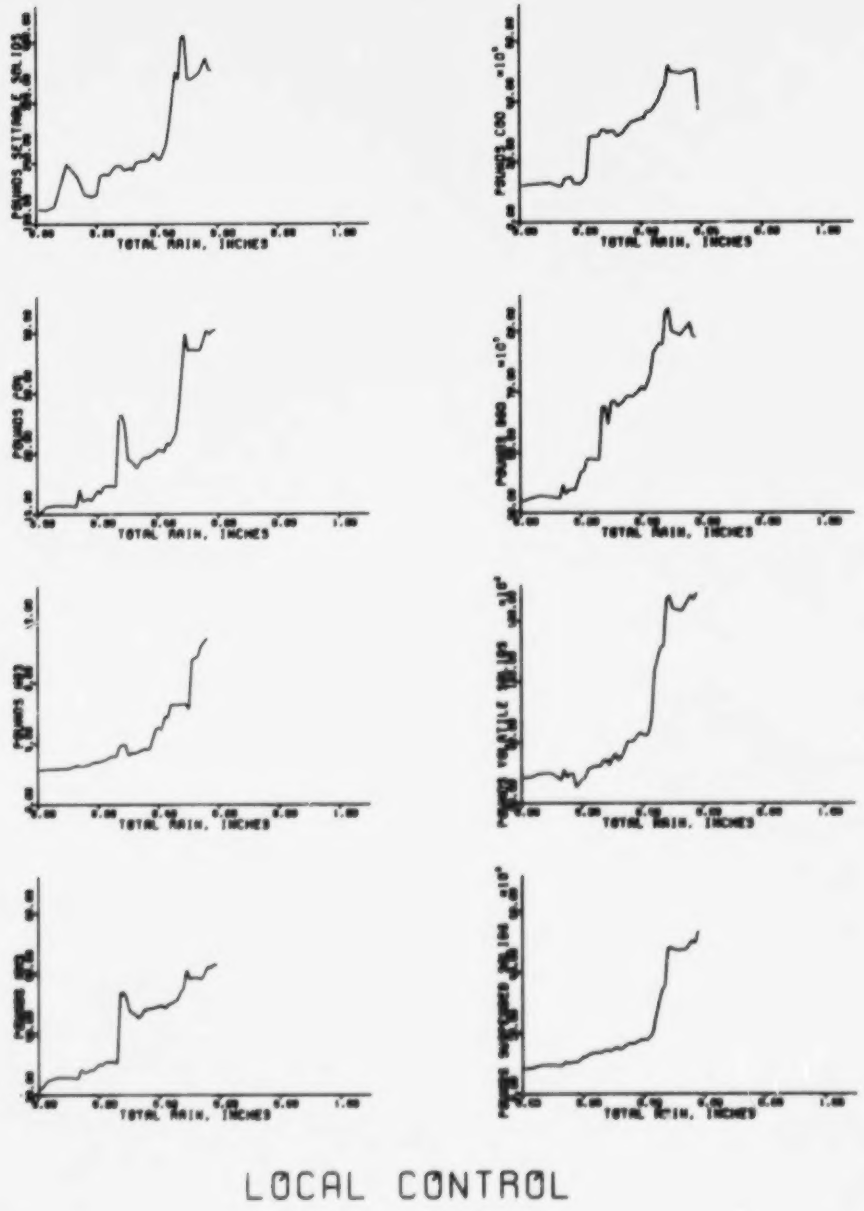
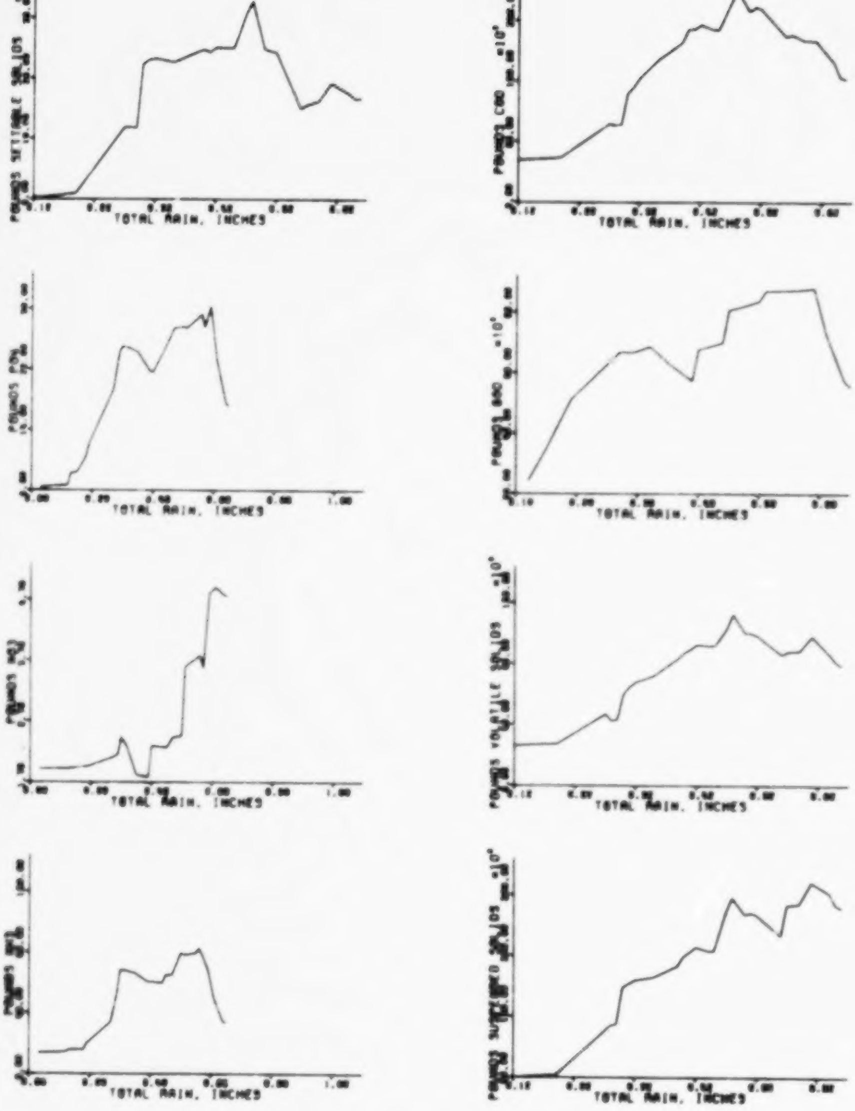


FIGURE 106

LOADING TRENDS DURING LOCAL CONTROL



SUPERVISORY CONTROL

FIGURE 107

LOADING TRENDS DURING ADVANCED CONTROL

Table 42. COMPARISON OF LOADING PEAKS

Parameter	Peak Value in Pounds [a]	
	Local Control	Advanced Control
Settleable Solids	400	360
Chemical Oxygen Demand	50,000	24,000
Phosphate	38	30
Biochemical Oxygen Demand	9,000	8,000
Nitrate	12	5
Volatile Suspended Solids	18,000	10,000
Ammonia	70	60
Suspended Solids	50,000	27,000

[a] After smoothing by moving average technique

Overall System Performance

CATAD total system performance is summarized in Figure 108. The figure combines volume reduction performance for the various control modes and average loading performance for advanced control on one page and relates these factors to total rainfall.

The figure shows that as storm intensities increase, the relative performance improvement diminishes with the more improved control systems because the maximum amount of additional storage is limited by the volume within the collection system. This storage limit, unless modified by construction of additional regulator stations,external storage tanks, or detention basins, will always have a lesser impact as storm intensities and inflows increase well beyond the storage capacity.

The performance figures and tables show that adding supervisory control reduced overflows 35-50 percent. Adding automatic control strategies improved these reductions to over 90 percent. Unusually dry weather conditions in the Seattle area during the automatic control period have limited the amount of data for comparisons. Therefore, there is some conjecture that future storms will lower the automatic control performance curve. However, at the same time, an optimizing model is being developed to provide a degree of prediction not presently available, which will, hopefully maintain a performance of at least 80 percent annual overflow volume reduction. The model can also be used as a design tool so that if even greater overflow reduction is desired, the model can predict overflow volumes and performance by simulating storm conditions and system response.

The success of this application of total systems management concepts is aided by the improved surveillance afforded by a continuous monitoring capability. But the greatest part of the improved performance is due to the ability (under either supervisory or automatic control) to locate portions of the sewer system which can be utilized for storage, thereby allowing overburdened portions of the system to flow more freely. Exact performance percentages cannot be directly transferred from this system to any other collection system because of the variability of regulating equipment and characteristics of the drainage basins and collection systems. However, the assurance of a vastly improved combined system operation with improved automated control techniques is clear. The next section will discuss the cost of this type of control system and some of the intangible benefits which can be expected.

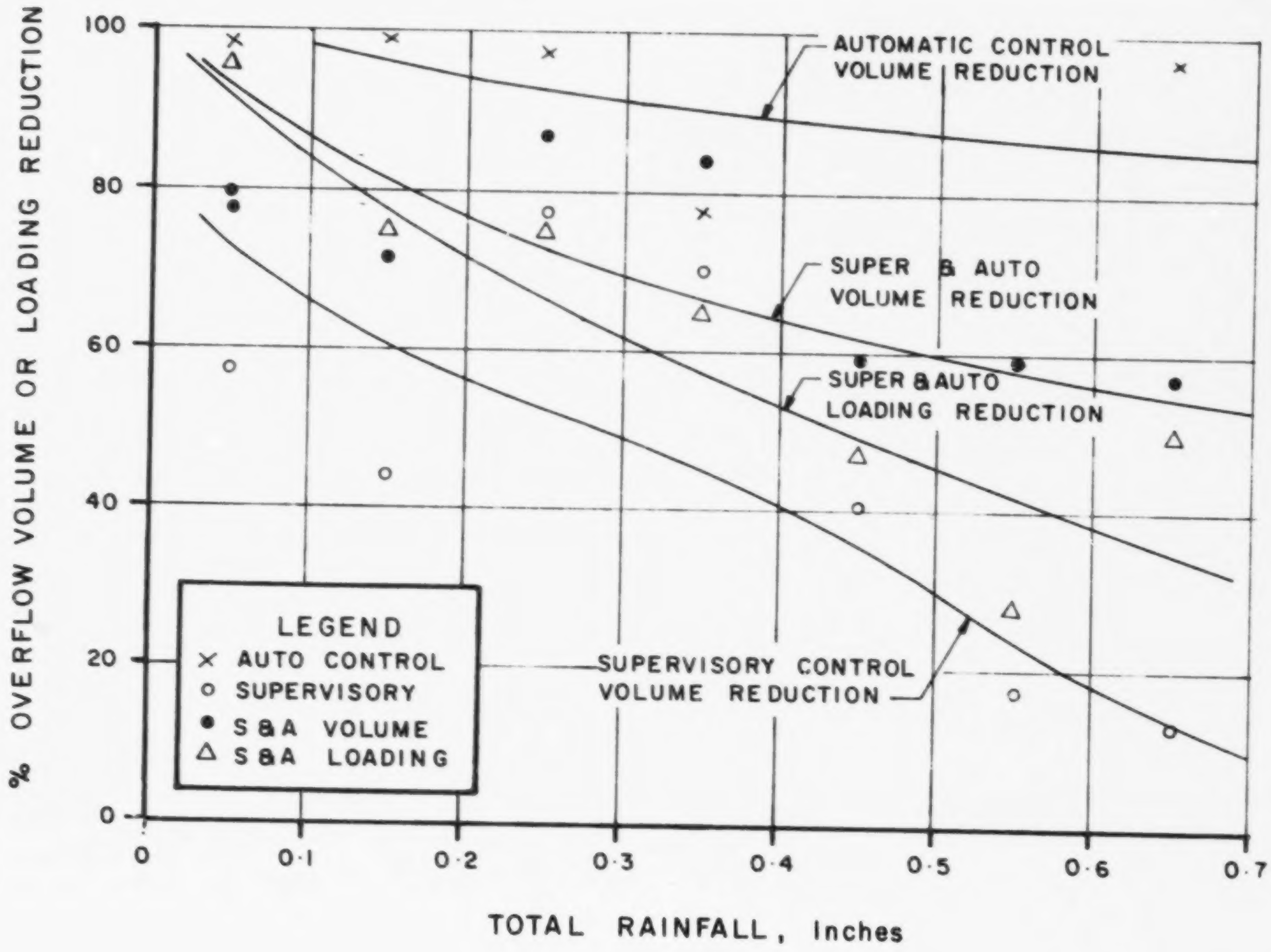


FIGURE 108

SYSTEM PERFORMANCE SUMMARY

SECTION XI

COSTS AND BENEFITS

INTRODUCTION

The previous section discussed water quality improvements resulting from CATAD automatic sewage collection system control. Residual effects on the receiving water also result from the many sewer improvements made between 1962 and 1971. These area sewer improvements are itemized in Table 43.

Table 43. METRO COMBINED SEWER AREA IMPROVEMENTS

Area[a]	Total Cost (x1000)
Elliott Bay Interceptor	$20,957
West Point Treatment Plant	13,816
West Point Outfall	1,229
North Interceptor	1,594
West Duwamish Interceptor	3,482
Alaskan Way Interceptor	3,176
	$44,254[b]

---

[a] "Interceptor" may include facilities such as pump or regulator stations.

[b] Total cost is 37 percent of 1960-1970 construction plan.

The interim report (12) listed many water quality improvements of the total construction program. Beginning in 1967, the CATAD project added improvements costing approximately five percent of the combined sewer work. In addition to the Metro work, in 1967 the City of Seattle began a $78 million partial sewer separation project which affected approximately 25 percent of the combined sewers within the CATAD study area.

PROJECT COSTS

The CATAD project was largely stimulated by a $1.4 million Federal demonstration grant from the Environmental Protection Agency -- 53.6 percent of the total project cost. A breakdown of eligible costs for this study is shown in Table 44.

Table 44. ELIGIBLE PROJECT COSTS

Project	Contract	Engineering	Total
Lake City Tunnel Regulator	$ 143,700	$ 42,300	$ 185,900
Denny Way Regulator	502,000	57,100	559,100
CATAD	864,800	433,700*	1,298,500
Regulator Controller Mods	36,500	4,300	41,800
Automatic Samplers	40,500	4,500	45,000
Interface at Remote Stations	145,700	293,700	439,400
Equipment	20,400	1,800	22,200
Report Productions	----	20,000	20,000
Subtotal	$1,754,600	$857,300	$2,611,900
Legal			2,200
TOTAL	$1,754,600	$857,300	$2,614,100

* Includes $356,200 for engineering and $77,500 for programming.

Final project costs can be compared to the initial cost estimates detailed in Table 43. The most important changes from the initial estimates involved reallocating funds for regulators and applying contingency and other monies for programming and engineering work.

Additional construction grant funds totaling $536,860 were applied to regulator stations constructed or rebuilt during the three-year span of this contract. Telemetry and control equipment allowing the CATAD system to interface with remote stations was considerably less expensive installed in new stations as compared to modifying existing stations with the same equipment. The incremental hardware cost for remote control on newly constructed or rebuilt stations is slightly over $13,000 versus $25,000 to modify existing stations. Table 44 shows that engineering and programming costs for the CATAD project, at 32.8 percent, are unusually high in comparison to many construction jobs. However, this was a research and development project, and such costs are expected in developing new and unusual concepts. The table also shows the high engineering cost for interfacing at remote stations; nearly twice the actual contract cost. Metro assigned consultants to research and record the existing controls at all remote stations. Precise design specifications were complicated by the basic control differences at each of the sixteen remote sites. Identical control components and functions at each station would have reduced interfacing costs. Similar interfacing equipment designed into a new station would accrue a fraction of the engineering costs reported above.

Any agency considering construction of a CATAD-type total management system must consider the cost of remote control regulators at every major control point in the collection system. Reduced overflow volume resulting from installation of dynamic mechanically controlled gate regulators is shown in Figure 105. Table 45 shows all costs associated with regulating stations, telemetry system, and all control and computer equipment acquired at the various consoles. On this basis, total project costs were $5.2 million versus $2.6 million eligible project costs previously listed.

Table 45. TOTAL SYSTEM COSTS[a]

Project	Construction Including State Tax	Engineering & Technical Services	Total Cost
Computer & Interfacing	$1,573	$1,111[b]	$2,684
West Duwamish Regulators	597	78	675
Hanford Street Regulator	362	56	418
Lander Street Regulator	321	49	370
Connecticut Street Regulator	201	31	232
King Street Regulator	120	19	139
Denny Way Regulator	502	57	559
Lake City Regulator[c]	144	42	186
Grand Total	$3,820	$1,443	$5,263

---

[a] Multiply all costs by 1000

[b] Includes $356,000 programming

[c] Added to project, not directly on main interceptor

The largest single CATAD system contract was for computer hardware, telemetry and control equipment located at the central station and at the remote stations. Table 46 itemizes these hardware costs which a municipality may expect to pay for a centralized computer control system. Adding computer monitoring and control to each station in the CATAD system cost $15,000 for station modifications plus $10,000 for a telemetry control unit. Improvements in electronic component miniaturization would greatly reduce the purchase costs for similar equipment today.

Table 46. HARDWARE COST DETAILS

Item	Cost (1968 dollars)
Process Control Computer	$ 165,870
Air Conditioning (Cooling tower system excluded)	5,613
Input/Output Terminal	109.711
Water Quality Interface	1,964
Peripheral Equipment	122,038
West Point Satellite Terminal	41,234
Telemetry Control Units	
w/commanding - 28 @ 9,214 =	257,992
w/o commanding - 8 @ 9,170 =	73,360
Central Operator's Console	182,165
Renton Satellite Interface	16,257
Spare Parts	36,967
Hardware Programming	148,397
TOTAL	$1,161,568

Construction cost for a new regulator station with motor-driven gates and local controls has averaged approximately $200,000. Other cities have installed less complicated balloon-type regulator gate structures at significantly lower cost. However, Metro's regulator structures are above ground, provide easy access for maintenance and operation, and often enhance the surrounding areas (see Figures 6 and 7).

MAINTENANCE AND OPERATING COSTS

Remote station and central station operating and maintenance costs are shown in Table 47. Regulator station maintenance and operation totaled $202,000 annually or $13,500 per regulator. An unusual central station maintenance and operation cost item is the $7,300 annual building rental cost. This cost item has been reported in few, if any, other combined sewer overflow control project reports. As noted, capital amortization costs may be added to maintenance and operation expenses for comparisons between projects. CATAD system central control facilities alone ($2,614 million) would cost $225,000 per year at an amortization figure of 6 percent for twenty years. Adding remote regulator stations increases the amortization of $5.26 million to an annual cost of $452,600.

Table 47. OPERATING - MAINTENANCE COSTS

Cost Item	Labor & Fringes	Utilities	Other	Total
Remote Station				
Operation	$ 87,960	$62,080	$ 1,360	$151,400
Maintenance	35,920	---	14,880	50,800
Subtotal, Remote Costs	$123,880	$62,080	$16,240	$202,200
Central Station				
Operation	$ 37,020	$ 3,860	$ 7,320[a]	$ 48,200
Maintenance	19,200	---	---	19,200
Subtotal, Central Costs	$ 56,220	$ 3,860	$ 7,320	$ 67,400
TOTAL, all phases	$180,100	$65,940	$23,560	$269,600[b]

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[a] About 75 percent of this cost is building rental.

[b] Amortization of capital: $2.6 million @ 6 percent for 20 years would add $224,000/year.

With capital and operating costs now itemized, some comparisons can be made between the CATAD system and other alternative solutions to the combined sewer overflow problem. The volume of combined sewer overflow captured annually can be determined from Figure 105 and compared to overflow amounts for the various control systems with average annual rainfall amount shown on the figure. Known costs, drainage area and annual overflow volume estimates provide the basis for Table 48.

Table 48. AVERAGE OVERFLOW VOLUMES FOR CONTROL MODES

MG per Storm Avg. Overflow	x 150 Avg. Storms Year	Annual Reduction Percent	Control Phase
12.36	1850	--	Static Reg.
7.68	1150	38	Dynamic Gate Reg.
4.20	630	66	Supervisory Cont.
0.41	62	97	Automatic Control

The same techniques were applied to compare other overflow problem solutions.

Table 49 shows that the CATAD project compares well with other methods of combined sewer overflow control. Comparisons should be viewed with some caution because most of the other projects are designed to handle essentially all overflow volumes. (Refer to "Percent Overflow Captured" column.) The low per-acre costs of centralized control projects in Minneapolis and Seattle would undoubtedly be considerably greater if required to achieve the capture percentage of the other listed solutions. The Minneapolis system seems least expensive; however, cost data is difficult to derive from the Minneapolis report (10). Minneapolis' supervisory control system is expectedly less costly than Seattle's automatic control system. Cost per thousand gallons of overflow captured and treated is also less for the centralized control projects. High rate filtration and rotary screening have a very low cost because of the very high estimated combined sewage capture volume. For an area 1/50 of the CATAD project, rotary screening estimates annual overflow capture equal to one third of the estimated overflow amount from the entire 13,000 acres.

FEASIBILITY OF CENTRALIZED CONTROL

Municipalities considering centralized control systems should realize that many research and development costs might not be encountered because future projects can profit from the experience of Seattle and other cities which have adopted some level of total systems management. In addition, costs of many of the electronic components utilized in this system are rapidly dropping while labor, utility and other costs are increasing. A detailed feasibility study must take all these factors into account.

Some comparisons can be made between the CATAD total systems management concept and sewer separation as a solution to the combined sewer overflow problem. In a combined sewer system, the heavy load of solids and pollutants from street drainage, and other materials settled into the sewer lines during low flow periods are often washed from the trunk line to the interceptor line for treatment until the combined flow exceeds sewer capacity. In a separate system, these materials are transmitted directly from the storm drain to the receiving water. If control storage is sufficient, no storm drainage pollutants would escape from the combined sewer system. The interim report (12) estimated a 50 percent decrease in BOD loading for a partially separated area versus a combined sewer area.

Table 49. OVERFLOW SOLUTIONS AND COMPARISONS

Reference	Method/Region	Acreage	Cost/Acre[a] Capital	M&O	M&O+A[b]	Cost/ Thsnd. Gals.	Pct. Ov. Captured
(47)	Complete Separation	---	13,568	---	---	---	100[c]
(6)	Partial Separation (67%) Seattle	18,000	4,300	22			---
(20)	Storage and Treatment Chippewa Falls	90	6,778	81	672	3.20	94
(48)	Deep Tunnel Storage Chicago	132,000	6,600	---	---		100
(49)	Chemical Primary Treatment Detroit	3,990	1,103	96	191	1.04	99
(22)	Underwater Storage Tanks	15	6,160	300	837	12.68	---
(50)	Hi-Rate Filtration Seattle	250	3,320	129	385	.36	96
(51)	Rotary Screening Seattle	250	2,135	74	238	.22	96
(10)	Dispatching Control Minneapolis	30,000	58	---	---	.87	75
--	CATAD w/o Regulators Seattle Metro	13,120	199	5	22	.88	80
--	CATAD w/Regulators	13,120	401	21	55	.72	80

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a. Costs are estimates for broad comparisons only.
b. "A" stands for annual cost of capital recovery 20 years @ 6% interest.
c. Ignores fact of added loading due to stormwater.

Table 47 was derived from Figure 105 assuming an average storm rate of 0.225 inch per storm and an average of 150 storm events per year. Being conservative and accepting temporarily only a combined supervisory and automatic annual overflow estimate of (630 + 62)/2 or 350, the table shows that supervisory control replacing existing dynamic regulator gates provided an annual overflow capture of 800 million gallons per year (1150 minus 350). Since the entire 13,120 acres has an annual average overflow of 1150 million gallons in the dynamic regulator gate phase, an equivalent separation area to achieve the 800 million gallons removed by the CATAD system would require:

13,120 acres x 800 MG ÷ 1150 MG = 9110 acres

Next, a basic acreage cost for complete separation must be established. A 1967 cost of $2,171 per acre for partial separation has previously been reported (54), for cities of 500,000 population or greater. Recent actual costs for partial separation in the Seattle area are $4,300 per acres. An escalation factor can not be calculated:

$4,300 ÷ $2,171 = 1.98

Applying this factor to the complete separation cost from the same reference yields:

$13,568 x 1.98 = $26,874/acre

The estimate of $26,870 per acre for complete sewer separation is considered reasonable because it is well below the maximum reported value of $55,800 per acre (54) for partial and complete separation.

Using these cost estimates of $4,300 and $26,870 per acre for partial and complete separation, respectively, the equivalent costs for either separation level is:

9110 acres x $4,300 = $39,173,000 (partial)

9110 acres x $26,870 = $244,786,000 (complete)

Obviously much less than $245 million, spent for automatic model programming and additional storage tanks would provide an improved total systems management project able to meet or exceed any reasonable overflow reduction goal. CATAD-type centralized control systems compare even more favorably since sewer separation projects often result in overall loading reduction between 50 and 75 percent. CATAD cannot claim all overflow reductions which have been observed in the three-year study. Partial separation of about one-fourth of the study area has also contributed to the near 80 percent overall reduction in combined sewer overflows. Metro will evaluate additional computer optimization programs, more sewer separation, storage tanks, and other alternatives which may be implemented to obtain even greater future efficiencies.

BENEFITS

An on-line computerized monitoring system has a very large capacity for continuously collecting, processing and storing valuable data about collection system facilities and the reaction of this system or its components to storms and alternative control strategies. Centralized monitoring of many facilities results in a timely response to and analysis and correction of collection system problems. Large investments in transportable test equipment, and related costs resulting from the dispersed activities are eliminated.

Apart from the cost advantages already discussed, installing a CATAD-type centralized control system realizes some benefits which are intangible or difficult to quantify. Some of these benefits are:

1. Routine data handling capacity
2. Time-shared services
3. Flexibility
4. Increased system capacity
5. Improved plant operation
6. Receiving water improvement
7. Public relations effect

A well designed control system often includes spare data processing capacity which can be applied to solving common business or scientific problems. The available computer time might also be sold, if allowed, or traded with outside agencies or businesses to reduce total central system operating costs. Many service agencies, like Metro, perform several community functions. There are obvious advantages in controlling more than one function with the same centralized system.

A computer system is easily modified to meet changing population growth patterns, public attitudes or governmental policy. This inherent flexibility is also valuable because the system can respond to new discharge restrictions developed by governmental agencies. Computer data files are readily available to be scanned and analyzed to assist in design and control changes needed to meet new regulations. The system can be converted to optimize control of the modified equipment or strategies.

The centralized computer system can increase Metro effective dry weather capacity by relieving normal daily peaks in sewer flows. More uniform flow might stabilize some sensitive sewage treatment processes such as biological secondary sewage treatment, thereby improving overall plant efficiency.

Centralized system control provides a proven alternative to sewer separation as a solution for combined sewer overflow problems. If still required, costs of a more expensive solution such as sewer separation may be stretched out over a longer period of time, and possibly reduced in scale.

Receiving water improvements accomplished by overflow reduction using a centralized control system may have both short and long-term effects. Higher recreational or commercial water use can increase water body productivity. Greater fish catches or improved tourist trade brought about by cleaner waters may repay much of the investment in the computerized system.

Finally, there are benefits to be gained in public and governmental relations from the control facility's appearance and performance. The growing emphasis upon environmental impact and community involvement make it very important for a water pollution control agency to consider this intangible benefit of a computerized control facility.

SUMMARY

The CATAD system has met or exceeded nearly all its proposed objectives. The going has sometimes been rough; however, the assets gained and the performance of the system far outweigh development difficulties. Other municipalities should seriously consider centralized sewer system control as one of the most reasonable solutions to combined sewer overflow problems. In the Seattle area, a highly automated centralized control system, aided by sewer separation of a portion of the drainage area, has reduced combined overflows by nearly 80 percent. Other communities may find centralized control combined with other overflow reduction techniques will provide performance records equal to or greater than Seattle's. The information developed and available from the CATAD project and other control systems will help water pollution control administrators decide on the type and degree of control required for their communities.

SECTION XII

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SECTION XIV

GLOSSARY OF TERMS AND ABBREVIATIONS

access time - time required by computer to locate a word in core memory and transfer the word to a register.

ACU - Auxiliary Control Unit: cabinet containing electronics, relays, etc. located between TCU and station local control system.

address - name or number which identifies a particular storage location in the computer.

analog - the representation of a numerical quantity by some physical variable; e.g., translation, rotation, voltage or resistance.

as-built - engineering drawing completed after a facility is constructed, shows original design plus revisions made during construction.

ASCII code - American Standard Code for Information Interchange; a special eight channel paper tape code developed to facilitate data transmission between machines manufactured by different companies.

autoanalyzer - copywritten term referring to equipment which automates chemical tests on samples. After initial setup of equipment and sampling unit, no further human effort is needed other than interpreting a strip chart.

background - a low priority, unprotected processing area in a computer where batches of programs are compiled, tested and run without affecting other protected control and processing areas.

BCD - Binary Coded Decimal, a computer coding system.

benthal sediments - deposits on the bottom of a stream, often containing decaying material which removes oxygen from the stream.

binary - the representation of a numerical quantity by use of the two digits 0 and 1.

bit - abbreviation of binary digit: smallest possible unit of computer storage.

BOD - biochemical oxygen demand, a standard test used in assessing wastewater strength. The quantity of oxygen used in the biological-chemical oxidation of organic matter in a specified time under standard conditions.

buffer - a device which compensates for speed differences between two machines, permitting them to operate together.

bug - a mistake or malfunction in the design of a program or computer.

byte - a sequence of adjacent Binary Digits operated as a unit.

CATAD - Computer Augmented Treatment and Disposal system

CCU - CATAD control unit: cabinet same as ACU but located at pumping stations.

cfs - cubic feet per second, unit of quantity of liquid flow.

checkpoint - a point in time where computer processing is stopped, all machine variables, registers and background area copied to a rapid magnetic storage device so that a large foreground program can temporarily use all or a part of what is normally called background area.

COD - chemical oxygen demand, a standard rapid test of the strength of a wastewater. The COD determination provides a measure of the oxygen equivalent of that portion of the organic matter in the sample that is susceptible to oxidation by a strong chemical oxident.

core - computer storage area where binary data is represented by the direction of the magnetic field in each unit of an array of tiny donut-shaped rings (generally).

Coliform - bacteria found only in intestines of mammals, therefore used as an indication of the pollution level of a sample or body of water.

composite - placing samples from a continuously changing stream into one common storage point to test for an average value.

CPU - central processing unit: that portion of computer excluding input-output and external storage units, where arithmetic, logical, storage and control functions are centered.

CRT - Cathode Ray Tube: television, for visual data presentation.

DC - direct current, a form of electrical power.

debug - the process of eliminating a mistake or malfunction in the design of a program or computer.

demersal fish - the resident fish species for a particular water body.

DO - dissolved oxygen, the amount of gaseous oxygen dissolved into a liquid sample.

digital - the use of discrete numbers to a given base to represent all quantities in a problem or calculation. Most often all information is stored, transmitted or processed by a dual state condition; e.g., on-off, open-closed, true-false.

dwf - dry weather flow: normal sewer flow from domestic and industrial sources only.

dynamic regulator - a regulator which automatically makes adjustments in control settings by responding to water levels in the combined sewer or interceptor.

executive - a program, often supplied with a computer, which controls loading and relocation of all software (much unknown to the programmer) required to execute a job entered by a programmer.

fecal coliform, fecal streptococcus - bacteria associated with humans, refinements to coliform tests to eliminate animal sources when assessing the pollution level of a water sample.

first flush - heavy load of material, previously settled in sewers, which is washed along by the initial flow resulting from a storm.

fps - feet per second, a measure of velocity.

force main - a pressure pipe joining the pump outlet at a wastewater pumping station with a point of gravity flow.

FORTRAN - FORmula TRANslation; a programming system developed by IBM which converts mathematical statements into computer language.

gpad - gallons per acre per day, a measure of infiltration or leakage between a pipeline and its surroundings.

hard copy - a printed copy of machine output.

hardware - the physical equipment and devices which comprise a computer or computer system component.

head - distance in feet from a free liquid surface to some reference point (which may be a different liquid surface).

hydrograph - a graphical representation of liquid flow versus time with time as the horizontal axis.

interceptor - sewer which receives water from various traverse sewers and carries water to a point for treatment and disposal.

interface - a common boundary between parts of a computer system.

interrupt - a special signal which temporarily halts the normal operation of some computer job for the purpose of accomplishing another more important short task, after which normal operation resumes.

loading - the dry weight, in pounds, of some material that is being added to a process or disposed of to a receiving water.

logic - the science of combining electronic components in order to define the interactions of signals in an automatic data processing system.

mathematical model - the characterization of a process or concept in terms of mathematics, which allows the simple manipulation of variables in an equation to determine how the process would act in different situations.

mg/l - milligrams per liter, or the concentration of some chemical in a liquid. If a letter appears after "mg" it represents the chemical symbol; e.g., N for nitrogen, P for phosphorous.

mgd - millions gallons per day, a common term for quantity of wastewater flow.

modem - device which converts between computer recognized signals and tones transmitted over telemetry lines.

NH4, NO_3 - chemical shorthand for ammonia and nitrate in solution.

nutrient - is a major ingredient of a water or wastewater sample; e.g., ammonia nitrogen, nitrate-nitrite nitrogen, phosphate-phosphorous, or silica which may serve as growth media for micro-organisms, phytoplankton or zooplankton.

off-line - system and equipment under human operator control, not CPU control.

OGC - outfall gate controller: cabinet containing controllers and recorders relating to the outfall gate at a mechanical regulator station.

on-line - system and equipment under continuous automatic CPU control.

orifice plate regulator - a machined hole in a metal plate (usually horizontal) allows a flow only slightly in excess of trunk dry weather flow to enter the interceptor.

overflow - undesirable emergency relief of sewer system by direct transmission to receiving water generally without treatment.

outfall - pipeline which carries raw or treated sewage from the collection system or treatment plant to the receiving body of water.

parity - a term relating to whether a given word or character (group of digits) is even or odd. A single bit denoting the parity of a word is usually attached to that word so that quick tests can be made as to the validity of the data.

partial separation - removal of some portion of all the elements of storm drainage into a combined sewer; e.g., streets and parking areas only, leaving roof and foundation drainage to enter the combined sewer.

peripheral - specialized machines connected electrically to the computer for converting between binary and other data forms; e.g., cards, tapes, typed pages.

pH - a measure of the degree of acidity or alkalinity of a solution.

PO_4 - chemical shorthand for phosphate in solution.

priority - degree of importance assigned to some computer task.

psig - pound per square inch, gage: a measure of the pressure of a fluid or gas based on atmospheric pressure.

purging - the act of reversing flow or using high pressure liquid or gas to clear a pipeline of a plug of solids.

RAS - Random Access Storage: a technique in which the computer can find one bit of data as quickly as any other, regardless of its specific location in storage.

rational method - a means of computing storm drainage flow rates by use of the formula $A=ciA$; where c is a coefficient describing the physical drainage area, i is the rainfall intensity and A is the area.

real-time control - control of a system by using computers and timing such that the speed of response to the input information is fast enough to effectively influence the performance of that system.

register - device consisting of miniature electronic components including transistors, where a specific number of bits are stored and operated upon.

regulator - structure which controls amount of sewage entering an interceptor by storing in a trunk line or diverting some portion of flow to an outfall.

retroreflective - technique of sensing periodic light reflections from a constant light source bouncing off a mirror attached to a rotating device.

routine - a sequence of instructions which perform a specific function within a larger program.

routing - storing, regulating, diverting or otherwise controlling the peak flows of wastewater through a collection system according to some prearranged plan.

rule curve - a curve which relates storage and time for a given reservoir under different control conditions.

sag curve - a curve which describes the gradual drop to some minimum value followed by an increase to normal levels of the dissolved oxygen in a flowing stream following the addition of some oxygen demanding material such as sewage.

salt wedge - a wedge shaped volume of salt water beneath a body of fresh water where a river and ocean meet in an estuary area.

secchi disk - a disk, painted in four quadrants of alternating black and white, which is lowered by rope into a body of water. The measured depth at which the disk is no longer visible from the surface is a subjective measure of relative transparency.

sequential - samples taken at known time intervals and stored in separate labeled containers.

side weir - a regulator which is essentially a long slot cut into the side of a sewer. Normal dry weather flow continues through the sewer while the increased depth during a storm will allow excessive flows to exit through the slot to some alternate point as an overflow.

scan - the collection and storage of data from all points at all stations in system by computer.

scan time - time set by operator which establishes the interval from the beginning of one scan to the next.

simulation - representation of physical systems and phenomena by computers, models and other equipment.

siphon - a u-shaped pipe used to carry wastewater under some obstacle such as a stream or another pipe.

sluice gate - a vertically sliding gate of any shape used to control or shut off flow in a sewer or other channel.

software - the programs or instructions which often control the hardware to perform some computer operation or extend the capabilities of the system.

static regulator - a regulator which is either fixed or can be adjusted only by manual actions of a human operator.

storage - unfilled, enclosed volumes within or connected to a sewer system capable of accepting and retaining wastewater for a period of time.

subroutine - a compact set of instructions to perform some repetitive task quickly and return to a main program.

table - a collection of data in a form suitable for ready reference by a computer.

telemetry - data transmission over long distances via telephone or telegraph lines by electro-magnetic means.

TCU - Telemetry Control Unit: interchangeable electronic cabinets, convert between telemetry and station control signals (from ACU or CCU).

time sharing - use of a computer or device for two or more purposes during the same overall time interval, done by interspersing component actions in time.

total systems management - as applied to combined sewer systems, means using both the transporting and retention capacity of a sewer system to limit overflows.

trunk - large sewer which receives wastewater from tributary branch sewers serving generally one drainage area.

trawl - a fish catching technique using nets pulled along a river bottom (net sometimes also reaches to the surface) by boat.

up-dating - the art of bringing information up to the correct time or value.

wastewater - the spent water of a community, including domestic, industrial and commercial water-carried solids plus storm or other water sources. Replacing the term sewage.

word - a set of 16 or more bits stored and transferred as a unit by the computer.

write - to transfer information, usually from main storage to an output device.

SECTION XV

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APPENDIX A

REMOTE STATION DATA

Table A-1: Regulator Station Construction Costs

Table A-2: Pumping Station Construction Costs

Table A-3: Basin Area - Hydrograph Data

Table A-1

REGULATOR STATIONS

Station Name[a]	Facility No.	Primary Segment Location	Computer Reference	Telemetry Circuit	Floor Space Square Feet	Construction Cost-dollars	Contract Yr. Compl.
Brandon (3)	220	S. Elliott Bay	10	2	180	110,600[b]	1972
Chelan	420	W. Duwamish	5	1	140	70,600	1967
Connecticut (2)	560	N. Elliott Bay	16	6	410	191,000	1971
Denny-Lk. Union[c]	620	N. Elliott Bay	19	6	390	240,000	1969
Denny-Local[c]	600	N. Elliott Bay	18	6	390	240,000	1969
Dexter Avenue	800	North Trunk	21	4	1530	454,000	1971
Eighth Avenue So.	470	W. Duwamish	1	1	170	63,700	1967
Hanford #1	500	Hanford-Elliott	13	6	190	110,000	1968
Hanford #2 (2)	530	Hanford-Elliott	14	6	480	343,000	1971
Harbor	400	W. Duwamish	4	1	200	75,400	1967
King Street	580	N. Elliott Bay	17	6	220	114,000	1971
Lk. City Tunnel(2)	710	North Trunk	25	4	780	137,400	1969
Lander	540	N.Elliott Bay	15	6	800	305,000	1971
Michigan (3)	240	S. Elliott Bay	9	2	220	136,700[b]	1972
Norfolk (2)	260	S. Elliott Bay	7			139,700[b]	1973
W. Michigan	450	W. Duwamish	3	1	130	56,700	1967

a. Numbers in parenthesis refer to no. of units, if station components are at multiple locations

b. Cost does not include facilities from 1935 construction, but does include 1972 revisions

c. Both stations at one physical site, cost and floor space allocated evenly.

Table A-1 (cont'd.)

REGULATOR STATIONS

Station Name	Connecting Sewer Diameter-Inches				Gate Size-Inches[c]			Drive Mechanism
	Trunk	Outfall	Interceptor	Transfer	Regulator	Outfall	Bypass	
Brandon	40x66[a]	50x78[a]	60	12	20x20	48x48	48x30	Motor
Chelan	54	54	42	36	36d	54x54	30x54[b]	Motor
Connecticut	72	72	96	36	36x36	84x60	72d	Hydraulic
Denny-Lake Union	60	60	102	21	21d	48x48	24x184[b]	Motor
Denny-Local	42	42	102	18	18x18	24x24	24x48[b]	Motor
Dexter Avenue	84	48	48	N/A	84x84	48x360[b]	84x66	Hydraulic
Eighth Avenue S.	48	36	36	24	24x24	36x36	28x36[b]	Motor
Hanford #1	150x100[a]	120	N/A	N/A	N/A	96x84	40x96[b]	Hydraulic
Hanford #2	150x100[a]	150x100[a]	96	48	48x48	144x96	96x84	Motor
Harbor	36	54	21	N/A	24x24	54x54	48x84[b]	Motor
King Street	48	48	96	30	30x24	60x36	24x120[b]	Motor
Lk. City Tunnel	96	N/A	108	N/A	96x96	N/A	N/A	Hydraulic
Lander	96	96	96	36	36x36	84x60	96x84	Hydraulic
Michigan	72x102[a]	72x102[a]	60	24	20x24	96x60	42[b]	Motor
Norfolk	84	84	42	42	60x24	54x48	36x72	Motor
W. Michigan	24	24	42	10	10d	24d	24d[b]	Motor

a. Horseshoe shaped sewer cross-section

b. Dimension of opening - no gate

c. Gates are actually all rectangular. Size refers to opening behind gate which is the critical dimension for computing flows.

Table A-2

PUMPING STATIONS

Station Name	Facility No.	Primary Segment Location	Computer Reference	Telemetry Circuit	Floor Space Square Feet	Construction Contract	
						Cost-dollars	Yr. Compl.
Bellevue	1160	Bellevue-Mercer Is.	30	5	1020	160,000	1965
Belvoir Place	100	Montlake University	23	3	1500	374,000[a]	1971
Duwamish	200	S. Elliott Bay	11	2	4900	1,134,000	1969
E. Marginal	250	S. Elliott Bay	8	2	1790	192,100	1964
E. Pine	130	Montlake University	22	N/A	700[d]	62,000[b]	1932
Heathfield	1130	Issaquah East Lake	34	5	400	163,000	1965
Henderson	150	S. Valley	6	N/A	1000[d]	64,000[b]	1934
Interbay	650	N. Elliott Bay	20	6	9000	1,486,100	1967
Juanita Heights	1020	Kirkland	36	4	1480	259,000	1969
Kenmore	740	Sammamish-Kenmore	27	4	500	207,500	1966
Kirkland	1090	Kirkland	37	5	1420	167,800	1966
Matthews Park	720	North Trunk	26	4	20,000	3,493,000	1967
N. Mercer Island	1210	Bellevue-Mercer Is.	32	5	2700	712,900	1970
Rainier Avenue	140	Rainier-Hanford	12	2	1100	717,500	1972
Renton S.T.P.	1230	Treatment Plants	29	5	30,000	3,500,000[c]	1965
S. Mercer Island	1220	Bellevue-Mercer Is.	33	5	940	179,800	1965
Sweyolocken	1150	Bellevue-Mercer Is.	31	5	1490	216,200	1965
Thirtieth Ave.N.E.	110	Montlake University	24	3	2100	385,000[a]	1971
W. Marginal Way	440	W. Duwamish	2	1	2080	262,000	1967
Wilburton	1140	Issaquah Eastlake	35	4	940	154,900	1965
West Point S.T.P.	660	Treatment Plant	28	3	35,800	4,000,000[c]	1966

a. Cost includes estimated value of facilities constructed in 1940's.
b. Estimated cost plus value of new pumps not yet installed, stations to be remodeled 1971-73.
c. Estimated value of pumping facilities within sewage treatment plant.
d. Estimated floor space, drawings not available.

Table A-2 (cont'd.)

PUMPING STATIONS

Station Name	No. Pumps Installed		Total Pumping Capacity - MGD		Rated Pump Head, Feet	Bypass Dia.-Inches
	Initial	Ultimate	Initial	Ultimate		
Bellevue	3	3	13.8	13.8	90.0	24
Belvoir Place	3	3	15.0	15.0	23.0	36
Duwamish	3	3	150.0	150.0	17.5	2 @ 36
E. Marginal	2	3	20.0	44.0	16.4	36
E. Pine	2[a]	-	4.3	-	90.0	24
Heathfield	2[a]	-	6.0	-	180.0	8
Henderson	2[a]	-	7.2	-	19.0[b]	60
Interbay	3	3	180.0	180.0	39.0	72
Juanita Heights	3	4	11.0	16.0	122.0	N/A
Kenmore	3[a]	-	12.0	-	32.0	N/A
Kirkland	3	3	12.0	12.0	187.0	48
Matthews Park	3	6	93.0	186.0	77.0	5 @ 24x24
N. Mercer Island	3	4	7.8	10.5	149.0	24
Rainier Avenue	3	3	9.0	12.0	41.0	72[b]
Renton S.T.P.	3	6	192.0	513.0	42.0	96
S. Mercer Island	3	3	18.0	18.0	63.3	24
Sweyolocken	3	4	20.4	27.2	75.0	30
Thirtieth Ave. N.E.	3	3	18.0	18.0	42.0	36
W. Marginal Way	3	3	24.3	24.3	20.0	N/A
Wilburton	2	3	8.0	12.0	110.0	24
West Point S.T.P.	4	4	432.0	432.0	17.7	2 @ 84

a. No ultimate data included, station due for remodeling

b. Estimated head, plans not available

APPENDIX A
TABLE A-3
BASIN AREA - HYDROGRAPH DATA

STATION	AREA TOTAL	ST. MILES SEPARATED	MAX. FLOW cfs	PEAK TIME Min.
West Michigan	0.334	-	446	21
8th Avenue So.	0.512	-	780	18
Harbor	0.692	-	842	23
Chelan	1.775	-	1640	28
Norfolk	5.30	4.70	1420	29
Michigan	1.172	-	1324	24
Brandon	0.266	-	436	18
Hanford	6.84	2.84	5630	55
King	0.394	-	593	20
Connecticut	1.290	-	1570	22
Lander	0.783	-	1080	20
Denny-Local	0.380	-	575	18
Denny-Lake Union	1.866	-	2087	23
TOTAL	20.508	7.50		

APPENDIX B

DATA MONITORED AT STATIONS

Table B-1: Data Point or Contact Monitored

Table B-2: CATAD Interface Function Definitions

Table B-3: Classification of Remote Terminals

Table B-1

DATA POINT OR CONTACT MONITORED (see Table B-2 for codes used)[b]

Regulator Name and Gate(s) in Use[a]	[a] Type		ROR-2	RCR-2	CLR-3	OFR	ACR	IAR	EGR	ROAUX	RCAUX	RSSAUX	OSSAUX	OOAUX	OCAUX	OACR	OIAR	OEGR	OBOR		FPSR	EHR1	EHR2	THR-1	THR-2	SLR-2	SFR-2	RLR-X	CLOR	APG1-2	APG2-2		RNG	24VR	SAR	EPFR	SMCR									FR	BLSS		BG POS	OG POS	INT LEV	EH1 LEV	TRNK LEV	STPT POS	TIDE LEV	EH2 LEV				
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		24	25	26	27	PC	PC	PC	PC	28	29	30	31	32	33	34	35	36	37	38	39	40		1	2	3	4	5	6	7	8	9	10	11	
Denny way - Local Outfall/Regulator	3		x	x	x	x				x	x	x	x	x	x							x					OOR-2	OCR-2	x																		x		x	x		x	x							
Dexter Ave. Regulator	4		x x	x	x	x	x	x		x	x	x							x		x	x		x						x						x											x		x		x	x	x							
Hanford St. No. 1 Regulator	4		x	x	x	x	x	x	x	x	x	x									x	x	x		x													x									x		x		x	x	x			x				
Lake City Tunnel Control	4		x	x	x		x	x	x	x	x	x									x	x																x									x		x		INT NO.	x	x							

a. See Table B-3 for explanation of letter/number codes

b. x indicates the contact is checked unless a different relay code is listed

Table B-1

DATA POINT OR CONTACT MONITORED
(see Table B-2 for codes used)[b]

Regulator Name and Gate(s) in Use[a]	Type[a]		ROR-2	RCR-2	CLR-3	OFR	ACR	IAR	EGR	ROAUX	RCAUX	RSSAUX	OSSAUX	OOAUX	OCAUX	OACR	OIAR	OEGR	OBOR		FPSR	EHR1	EHR2	THR-1	THR-2		SLR-2	SRR-2	RLR-3	CLOR	APS1-2	APC2-2		RNG	24VR	SAR	ERFR	SMCR								FR	RLSS		RG POS	OG POS	INT LEV	EH1 LEV	TRNK LEV	STPT POS	TIDE LEV	EH2 LEV				
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		24	25	26	27	PO	PC	PC	PC	28	29	30	31	32	33	34	35	36	37	38	39	40		1	2	3	4	5	6	7	8	9	10	11	
Norfolk St. Outfall/Regulator	1		x	x	x	x	x	x	x	x	x	x	x	x	x				x			x					x	x	x		x	x			x												x		x	x	x	x	x	x	x					
Chelan Ave. Outfall/Regulator	1		x	x	x	x	x	x	x	x	x	x	x	x	x							x					x	x	x		x	x			x												x		x	x	x	x	x	x	x					
Lander St. Bypass/Outfall/Regulator	1		x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x					x	x	x		x	x			x			x									x		x	x	x	x	x	x	x					
Connecticut St. Bypass/Outfall/Regulator	1		x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x					x	x	x		x	x			x		x	x									x		x	x	x	x	x	x	x					
Denny Way L.U. Outfall/Regulator	1		x	x	x	x	x	x	x	x	x	x	x	x	x							x					x	x	x		x	x		x	x												x		x	x	x	x	x	x	x					
Brandon St. Outfall/Regulator	2		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x					x	x	x		x	x			x												x		x	x	x	x	x	x	x					
Michigan St. Outfall/Regulator	2		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x					x	x	x		x	x			x												x		x	x	x	x	x	x	x					
Hanford St. No. 2 Outfall/Regulator	2		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x							x		x	x	x		x	x			x												x		x	x	x		x	x	x					
Harbor Ave. Outfall/Regulator	3		x	x	x	x	x	x	x	x	x	x	x	x	x							x							x		OOR-2	OCR-2															x		x	x	x	x	x		x					
W. Michigan St. Outfall/Regulator	3		x	x	x	x	x	x	x	x	x	x	x	x	x							x							x		OOR-2	OCR-2															x		x	x	x	x	x							
8th Ave. South Outfall/Regulator	3		x	x	x	x	x	x	x	x	x	x	x	x	x							x	x						x		OOR-2	OCR-2															x		x	x	x	x	x		x	x				
King Street Outfall/Regulator	3		x	x	x	x	x	x	x	x	x	x	x	x	x							x							x		OOR-2	OCR-2															x		x	x	x	x	x		x					

a. See Table B-3 for explanation of letter/number codes
b. X indicates the contact is checked unless a different relay code is listed

Table B-1

DATA POINT OR CONTACT MONITORED
(see Table B-2 for codes used)[b]

Pumping Station Name[a]	Type[a]		PSR1-1	PSR2-1	PSR3-1	PSR4-1	ACR-1	IAR-1	EGR-1	PUR1-1	PUR2-1	PUR3-1	PUR4-1	PUR5-1	PUR6-1	WWLR-1	48VR-1	IGOR-1	STAR-1	BSDR-1	FPSR1-1	FHR-1	PSR5-1	PSR6-1	WWLR-2		SLR-2	SRR-2	RLR-3	WSR-1	APSI-2	RNG			WWFR-1	PRFR-1	24VR-1	OMR1-1	OMR2-1	OMR3-1	OMR4-1	OMR5-1	OMR6-1	OMR7-1	OMR8-1	FR	RLSS		PS4	PS5	PS6	EH lev	WW LEV	PP SIG LEV	PIS	FMPr1	FMPr2	PS2	PS3	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		24	25	26	27	PC	PC	PC	PC	28	29	30	31	32	33	34	35	36	37	38	39	40		1	2	3	4	5	6	7	8	9	10	11	
Kenmore	6		x	x	x		x	x	x	x	x	x				x						x	FFR-2	SFR-2	x			LR-2	x			x			x	x		x	x	x							x			FMPr3		x	x			x	x			
West Point T.P.	7						x		x	x	x	x	x								x														x	x											x		x				x		x	FLM		x	x	
Juanita Hts.	7		x	x	x		x	x	x	x	x	x							x											x					x			x	x	x	x						x						x		x	x		x	x	
Kirkland	7		x	x	x		x	x	x	x	x	x																		x		x			x	x		x	x	x							x						x		x	x		x	x	
Heathfield	7		x	x			x	x	x	x	x																			x					x	x		x	x	*							x						x		x	x		x		
Wilburton	7		x	x			x	x	x	x	x																			x					x	x		x	x	x							x						x		x	x	x	x		
Swevolocker	7		x	x	x		x	x	x	x	x	x																		x					x	x		x	x	x							x						x		x	x	x	x	x	
Bellevue	7		x	x	x		x	x	x	x	x	x																		x					x	x		x	x	x							x						x		x	x		x	x	
N. Mercer Is.	7		x	x	x		x	x	x	x	x	x							x											x					x	x		x	x	x							x						x		x	x		x	x	
S. Mercer Is.	7		x	x	x		x	x	x	x	x	x																		x					x	x		x	x	x							x		x				x		x	x		x	x	
Renton STP	7						x		x	x			x		x						x											x			x	x											x		x		x		x			FLM				

a. See Table B-3 for explanation of letter/number codes

b. X indicates the contact is checked unless a different relay code is listed

Table B-1

DATA POINT OR CONTACT MONITORED
(see Table B-2 for codes used)[b]

Pumping Station Name[a]	Type[a]	OMR 11-1	OMR 12-1	GSR 1-1	GSR 2-1	GSR 3-1	POVR 1-1	POVR 2-1	POVR 3-1	POVR 4-1	POVR 5-1	POVR 6-1	COVR-1	POVCR 1-1	POVCR 2-1	POVCR 3-1	125VR-1	FPSR 3-1	FPSR 2-1	FPSR 4-1	POVCR 4-1	POVCR 5-1	POVCR 6-1	COVCR-1		OMR9-1	OMR 10-1
		41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63		64	65
Interbay	2						X	X	X	X				X	X	X	X		X		X						
Matthews Park	3	X	X	X	X	X	X	X	X					X	X	X	X	X	X	X						X	X

a. See Table B-3 for explanation of letter/number codes

b. X indicates the contact is checked unless a different relay code is listed

Table B-1

DATA POINT OR CONTACT MONITORED
(see Table B-2 for codes used)[b]

Pumping Station Name[a]	Type[a]		PSR1-1	PSR2-1	PSR3-1	PSR4-1	A4R-1	IAR-1	ESR-1	PUR1-1	PUR2-1	PUR3-1	PUR4-1	PUR5-1	PUR6-1	WWLR-1	4HVR-1	ICOR-1	STAR-1	BSOR-1	FFSRI-1	EHR-1	DSR5-1	PSR6-1	WWLR-2	SLR-2	SRR-2	RLR-3	WSR-1	APGI-2	RNG			WWFR-1	PRFR-1	24VR-1	OMR1-1	OMR2-1	OMR3-1	OMR4-1	OMR5-1	OMR6-1	OMR7-1	OMR8-1	FR	RLSS	PS4	PS5	PS6	EH LEV	WW LEV	PP SIG LEV	PS1	FMPr1	FMPr2	PS2	PS3
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	PC	PC	PC	PC	[illegible]	29	30	31	32	33	34	35	36	37	38	39	40	1	2	3	4	5	6	7	8	9	10	11
Belvoir Place	1		x	x	x		x	x	x	x	x	x				x									x	x	x	x	x	x				x	x	x	x	x	x							x					x	x	x			x	x
30th Ave. N.E.	1		x	x	x		x	x	x	x	x	x				x			x			x			x	x	x	x	x	x				x	x	x	x	x	x							x				x x	x	x	x	x		x	x
Rainier Ave.	1		x	x	x		x	x	x	x	x	x				x	x		x			x			x	x	x	x	x	x				x	x	x	x	x		x						x			FLM	x	x	x	x			x	x
E. Marginal Way	1		x	x			x	x	x	x	x					x						x			x	x	x	x	x	x				x	x	x	x	x	x							x				x	x	x					
																																																		x	x	x	x			x	x
Interbay	2		x	x			x	x	x	x	x					x		x	x	x	x	x			x	x	x	x	x	x				x	x	x	x	x								x											
																																																		x	x	x	x	x	x	x	x
Matthews Park	3		x	x	x		x	x	x	x	x					x		x	x		x	x			x	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x		x											
																																																		x	x	x	x	x	x	x	x
Duwamish	4		x	x	x		x	x	x	x	x						x	x		x	x	x							x					x	x		x	x	x							x											
E. Pine St.	4		x	x	x		x	x	x	x	x					x						x							x					x	x		x	x	x							x				x	x		x	FLM		x	x
																																																		x	x		x			x	x
S. Henderson St.	5		x	x	x		x	x	x	x	x					x						x							x					x	x		x	x	x	x						x											
																																																		x	x		x	x		x	x

a. See Table B-3 for explanation of letter/number codes

b. X indicates the contact is checked unless a different relay code is listed

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS

ABBREVIATION	DEFINITION	REMARKS
I. COMMAND FUNCTION SETS (Contacts and relays in TCU)		
A. Regulator Gate Direct Control		
RO	Open regulator gate	
RC	Close regulator gate	
CL	Computer-Local command for regulator gate	-Closing of this command contact sets up interface circuitry that permits computer control of gate.
B. Outfall Gate Direct Control		
OO	Open outfall gate	
OC	Close outfall gate	
RL	Remote-Local command for outfall gate	-Same as CL except it is for outfall gate.
C. Setpoint Control		
SL	Setpoint lower	-Outfall Stations: Lower setpoint. Serves to indirectly open outfall gate and reduce storage. -Pumping Stations: Lower level signal (apparent water level) to pump controls.
SR	Setpoint raise	-Outfall Stations: Raise setpoint. Serves to indirectly close outfall gate and increase storage. -Pumping Stations: Raise level signal (apparent water level) to pump controls.
RL	Remote-Local command for setpoint	-Same as CL above. When command contact opens, setpoint control is returned to local constant setpoint.

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
I. COMMAND FUNCTION SETS (Contacts and relays in TCU) (Cont'd)		
D. Pump Direct Control (Kenmore PS only)		
L	Start lead pump)	-When command contact closes pump starts; when command contact opens pump stops.
FF	Start first follow pump)	
SF	Start second follow pump)	
RL	Same as CL above except for pumps	
FR	Telemetry failure relay	-It has contacts in the "Computer-Local" command circuit (CL and RL) of the TCU.
RLSS	Remote-Local selector switch	-It has contacts in the "Computer-Local" command circuit (CL and RL) of the TCU.
II. ANALOG FUNCTIONS		
RG pos	Regulator gate position	
OG pos	Outfall gate position	
INT Lev	Interceptor level	
TRNK Lev	Trunk level	
TIDE Lev	Tidal level	
STPT pos	Setpoint position	
EH Lev	Explosion hazard level	
WW Lev	Wet Well level	-Actual level measurement
PP Sig Lev	Pump program signal level	-CATAD signal to pump controller
FMPr	Force main pressure	
FLM	Flowmeter rate	
PS	Pump speed	

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
III. STATUS (ALARM & MONITOR) FUNCTIONS		
A. Command Report Back Relays. Contacts Close on Receipt of Command from Central Computer.		
LR	Lead pump relay	
FFR	First follow pump relay	
SFR	Second follow pump relay	
RLR	Remote-local relay	
ROR	Regulator gate open relay)	-Regulator gate direct command relays.
RCR	Regulator gate close relay)	
CLR	Computer local relay)	
OOR	Outfall gate open relay)	-Outfall gate direct command relays.
OCR	Outfall gate close relay)	
RLR	Remote local relay)	
SLR	Setpoint lower)	-Setpoint command relays. -Located in the setpoint command chain through to the outfall gate.
SRR	Setpoint raise)	
RLR	Remote-local)	
NOTE:	(for all group A relays) In addition to the report back contact functions, other contacts on these relays serve in the local control circuits. Thus the principal function of these relays is as interposing relays between the TCU command contacts and local control circuits.	
B. Operating Equipment Monitors		
APG	Pulse generator auxiliary relay	-Contact pulses when pulse generator (PG) in setpoint control circuit is operating.
COVCR	Crossover valve closed relay	-Contact closes when crossover valve in completely open as indicated by limit switch (Matthews only).

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
III. STATUS (ALARM & MONITOR) FUNCTIONS (Cont'd)		
COVR	Crossover valve opened relay	-Contact closes when crossover valve is completely open as indicated by limit switch (Matthews only).
OBOR	Outfall bypass gate open relay	-Contact closes when outfall bypass gate is unseated.
OC/AUX	Outfall gate closing relay	-Contact is closed when gate closing motor starter coil is energized.
OO/AUX	Outfall gate opening relay	-Contact is closed when gate opening motor starter coil is energized.
OMR	Operating mode relay	-Contact closes when pump station controls are operating in a particular mode.
OSS/AUX	Outfall gate starter selector switch relay	-Contact closes when HOA switch is in "AUTO" position and equipment is ready to operate or running.
PDVCR	Pump discharge valve closed relay	-Contact closes when pump discharge valve is completely closed as indicated by limit switch.
PDVR	Pump discharge valve opened relay	-Contact closes when pump discharge valve is completely open as indicated by limit switch.
PSR	Pump selector switch (PSS) relay	-Contact closes when pump motor starter HOA switch is in "AUTO" position.
PUR	Pumping unit running relay	-Contact closes when pump motor starter coil is energized.
RC/AUX	Regulator gate closing relay	-Contact is closed when gate closing motor starter coil is energized.
RLSS-3	"Remote-Local" selector switch stage	-(See RLSS in Section I.) Contact closes when switch is in "Local" position.
RNG	Rainfall gage relay	-Contact closes when rainfall gage pulses (indicating 0.01 inch of rainfall per pulse).
RO/AUX	Regulator opening relay	-Contact is closed when gate opening motor starter coil is energized.
RSS/AUX	Regulator gate starter (or operation) selector switch relay	-Contact closes when HOA switch is in the "AUTO" position and equipment is ready to operate.
WWLR	Wet well control selector (WWSS) relay	-Obsolete. See CLOR.
WWLR-2		-Contact opens to interrupt TCU FR signal. See CLOR.

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
III. STATUS (ALARM & MONITOR) FUNCTIONS (Cont'd)		
C. Emerjency Alarm Functions		
ACR	AC Control power relay	-Contacts close on loss of control power to operating control equipment.
BSDR	Bar screen differential relay	-Contacts close when difference in sewage level across the bar screen exceeds a preset amount.
CACR	CATAD a-c control power relay	-Contact closes on loss of control power to CATAD equipment (TCU, ACU, OGC & CCU).
CLOR	CATAD locked-out relay	-Closes when conditions in the remote station indicate loss of control by CATAD.
EGR	Emergency generator relay	-Contact closes when automatic transfer switch is in emergency power source position.
EHR	Explosion hazard relay	-Contact closes when concentration of explosive gases has reached an unsafe level.
ERFR	Equipment room flood relay	-Contact closes when sump level in equipment room is excessive.
FPSR	Fluid power system relay	-Contact closes on loss of pressure in fluid power systems including accumulator banks.
FR-3	Computer failure relay contact	-(See FR in Section I).
GSR	Generator set relay	-Contact closes on loss of a-c power from the generator sets.
IAR	Instrument air relay	-Contact closes on low pressure at instrument air receiver tank.
OACR	Outfall station a-c control power relay	-Contact closes on loss of control power to operating control equipment at outfall station.
OCACR	Outfall station CATAD a-c control power relay	-Same function as CACR
OEGR	Outfall emergency generator relay	-Same function as EGR.
OFR	Effluent overflow relay	-Contact closes when outfall gate off closed limit switch.
OIAR	Outfall instrument air relay	-Same function as IAR.

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
III. STATUS (ALARM & MONITOR) FUNCTIONS (Cont'd)		
PRFR	Pump room flood relay	-Contact closes on beginning of flooding in the pump room.
RACR	Regulator station a-c control power relay	-Same function as ACR.
RCACR	Regulator station CATAD a-c control power relay	-Same function as CACR
REGR	Regulator station emergency generator relay	-Same function as EGR.
RIAR	Regulator station instrument air relay	-Same function as IAR.
SAR	Service air relay	-Contact closes on low pressure at service air receiver tank.
SMCR	System master control relay	-Contacts close when master relay is not picked up.
STAR	Starting air relay	-Contacts close on low pressure at starting air receiver tank.
THR	Trunk high level relay	-Contact closes in influent (trunk) high level.
WSR	Water system relay	-Contact closes on low pressure of pumping unit seal water system (C2 or C2HP).
WWFR	Wet well flood relay	-Contact closes when flood level is reached in wet well. This is via a float switch operation.
24VR	24V d-c control power relay	-Contact closes on loss of 24V d-c power for setpoint stepping motor.
48VR	48V d-c control power relay	-Contact closes on loss of 48V d-c control power.
125VR	125V d-c control power relay	-Contact closes on loss of 125V d-c control power for main control circuit for pumps.

Table B-2. CATAD INTERFACE FUNCTION DEFINITIONS (Cont'd)

ABBREVIATION	DEFINITION	REMARKS
IV. EQUIPMENT DEFINITIONS		
CLSS	CATAD-Local Selector Switch	-Has contacts in the CLOR circuit. Contacts open when switch is in the "local" position.
WWSS	Wet well selector switch	-Obsolete. See CLSS.
ACU	Auxiliary Control Unit	-Houses relays and terminals.
CCU	CATAD Control Unit	-Houses relays, terminals and TCU.
MCC	Motor Control Center	-Motor starter and control panel.
MCP	Main Control Panel	-The main instrument panel in a station.
OGC	Outfall gate controller	-Special enclosure housing gate control instruments where there was no room in main control panel for this equipment.
TCU	Telemetry Control Unit	-Local computer interface/telemetry cabinet.
$\frac{\text{RNG}}{\text{a}}$	Raingage Contact	-Contact on raingage, provides pulse for each 0.01 inch of rainfall.

TABLE B-3

CLASSIFICATION OF REMOTE TERMINALS

Function	Type	Regulator Gate Direct Control	Outfall Gate		Separate Structures	Dual Trunks	Trunk Storage	Interceptor Storage
			Direct Control	Indirect Control				
Regulator	1	x		x			x	
Regulator	2	x		x	x		x	
Regulator	3	x	x					
Regulator	4	x	x	x		x	x	
Regulator	5	x						x

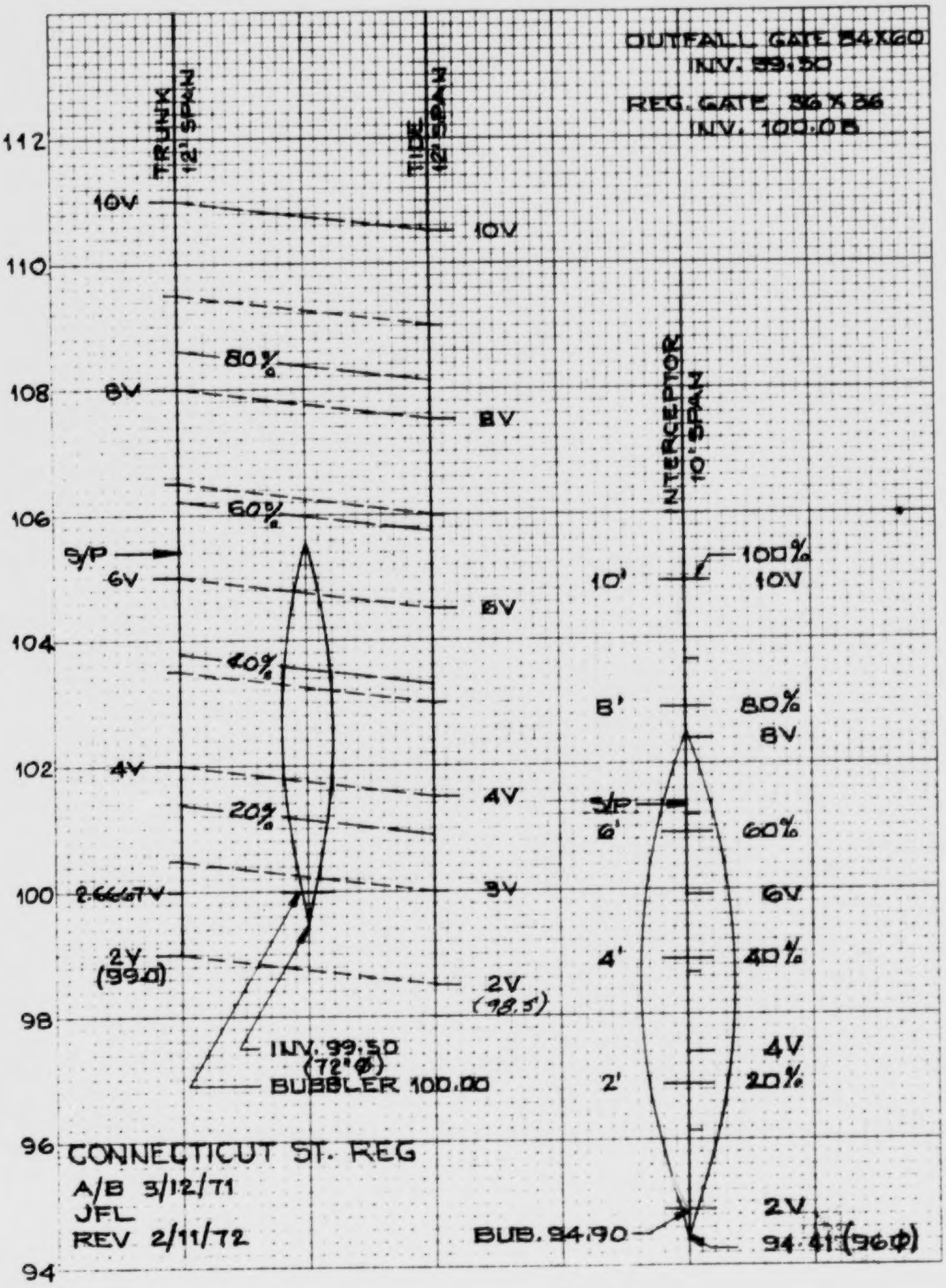
Function	Type	Three Electric Pumps	Four Electric Pumps	Six Electric Pumps	Three Gas Driven Pumps	Upstream Storage	Pump Control
Pumping	1	x				x	x
Pumping	2	x					
Pumping	3				x	x	x
Pumping	4			x		x	x
Pumping	5		x				

APPENDIX C

STATION EQUIPMENT CALIBRATION DATA

Regulator Instrument Calibration Sheet

Retroreflective Photo Sensor Schematic


OUTFALL GATE 54X60
INV. 99.50
REG. GATE 36 X 36
INV. 100.05
TRUNK
12' SPAN
TIDE
12' SPAN
INTERCEPTOR
10' SPAN
112
110
108
106
104
102
100
98
96
94
10V
10V
80%
8V
8V
60%
S/P
6V
6V
40%
4V
4V
20%
2.6667V
3V
2V
(99.0)
2V
(98.5')
INV. 99.50
(72"Ø)
BUBBLER 100.00
10'
100%
10V
8'
80%
8V
S/P
6'
60%
6V
4'
40%
4V
2'
20%
2V
BUB. 94.90
94.41 (96Ø)
CONNECTICUT ST. REG
A/B 3/12/71
JFL
REV 2/11/72

INSTRUMENT ADJUSTMENT

Connecticut Street Regulator

Trunk D/P - Span 144" H_2O
Elevate 0 to 2.66 VDC
Span 132" = 10.00 VDC, 5A(-),5B(1)

Tide D/P - Span 144" H_2O
Elevate 0 to 3.00 VDC
Span 126.0" = 10.00 VDC, 5G(-),5H(+)

Interceptor D/P - Span 120" H_2O
0 = 2.00 VDC
Span 120" = 10.00 VDC, 2E(-),2F(+)

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 23, 1972

Station: Connecticut Street Regulator

Contract No. 69-1

Dwg. Ref. E6

Function: Tide Level Xmitter

Tag. No. LX 203A

Instrument Type: Electronic D/P

Mfr. F&P

Location: MCP

Model No. 13D2495RB

Serial No. 6911A0869J11

INSTRUMENT DATA

Range Limits: 200" H_2O

Load Impedance:

Output Signal: 4-20 ma

Max. Overrange:

Air Supply:

Voltage Supply: 48vdc

Mounting: Rack

Calibrated Accuracy: 5%

Zero:

Span:

FIELD DATA

Datum Ref. MSL = 100.00 Ft.

Finished Grade Ref.El.

Location of Perm.Ref.

Invert El.of Sewer 99.50

Bubbler Tube El. 100.00

Transmitter Zero Setting

93.50 El. Ref.

Transmitter span Setting 12 Units ft.

or 93.5 to 11[illegible].5 Ft.El.

Signal Proportion:

0 ____ to ____ Ft.= 3-15 psi

or ____ to ____ Ft.= 10-50 ma

or 0 to 12 Ft.= 4-20 ma

Line Pressure ____ psi.

Scale

Remarks

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Tide Level Xmitter	1

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 2[illegible], 1972

Station Connecticut Street Regulator

Function Tide Level Signal Converter

Instrument Type Electronic I/I

Location MCP

Contract No. 69-1
Dwg. Ref. E6

Tag No. I/I 209A

Mfr. F&P

Model No. 50EK1000

Serial No. 6911A086-J24

INSTRUMENT DATA

Input Signal 4-20 ma

Set Points ---

Output Signal 4-20 ma

Set Point Dial Accuracy ---

Input Impedance 120 Ω

Mounting Rack

Voltage Supply 120-vac

Air Supply

FIELD DATA

Signal From LX203A

To LR207 & SP 209A

Input Span Setting:

4 to 20 ma

Output Span Setting:

4 to 20 ma

Remarks Fixed Calibration

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut Street Regulator Tide Level Signal Converter	2

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Regulator

Function Recorder

Instrument Type Electronic

Location MCP

Contract No. 69-1

Dwg. Ref. E6

Tag No. LR 207

Mfr. F&P

Model No. 51-4202BL02-BL02

Serial No. 6911A3713J3

INSTRUMENT DATA

Input Signal 4-20 ma

Input Impedance 250 Ω

Pens & Chart 3 pen 1 chart

Mounting Flush

Scale Length 5"

and/or Arc None

and/or Marking

Accuracy 5%

Chart Drive 1" /hr.

Response 120 ac

Voltage Supply

FIELD DATA

Signal From

Red - LX 202A
Green - LX 203 A
Blue - R/I 206 B

Remarks

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Recorder	3

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut Street Regulator
Function High Signal Selector
Instrument Type Electronic
Location MCP

Contract No. 69-1
Dwg. Ref. E6
Tag No. SP 209 A
Mfr. F&P
Model No. 55ES3512FA
Serial No. 6911A0869J20

INSTRUMENT DATA

Input Signal 4-20 ma
Input Impedance 250 Ω
Output Signal 4-20 ma
Load Impedance 0-750 Ω
Mode Adjustment:
Proportional
Reset
Rate
Auto-Manual
Output Meter 0-100%
Set Point - Man. Yes Auto No
Isolation ; input/output No
Mounting Rack
Available Contacts (No. of & Hi or Low)
None
Voltage Supply 120-vac
Remarks

FIELD DATA

Signal From LX203A, SP209B
To SP209G
Set Point Setting Hi Signal
Prop. Setting
Reset Setting
Rate Setting
Contact: 1st Hi
Low
2nd Hi
Low
3rd Hi
Low

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator High Signal Selector	4

INDICATING CONTROLLER

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Contract No. 69-1
Dwg. Ref. E-6
Station Connecticut Street Regulator
Function Set Point Signal Converter
Tag No. I/I 209B
Instrument Type Electronic I/I
Mfr. F&P
Location MCP
Model No. 50EK1000
Serial No. 6911A0869J29

INSTRUMENT DATA

Input Signal 4-20 ma
Set Points ---
Output Signal 4-20 ma
Set Point Dial Accuracy
Input Impedance 130 Ω
Mounting Rack
Voltage Supply 120-vac
Air Supply ---

FIELD DATA

Signal From SP209B
To SP209A
Input Span Setting:
4 to 20 ma
Output Span Setting:
4 to 20 ma

Remarks Fixed Calibration

DATE	BY	JOB NO.	TITLE	SHT NO
2/11/72	J.F.[illegible]	C200	Connecticut St. Reg. Set Point Signal Converter	5

TRANSDUCER & CONVERTERS

CALCULATION SHEET
METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 25, 1972

Station Connecticut Street Regulator
Function Electronic Trip
Instrument Type Electronic Alarm
Location MCP

Contract No. 62-1
Dwg. Ref. E6
Tag No. SP 209 C
Mfr. Foxboro
Model No. 63U-BT-OEJR-P
Serial No. 2234666

INSTRUMENT DATA

Input Signal 4-20 ma
Input Impedance 250 Ω
Output Signal Contact
Load Impedance
Mode Adjustment:
Proportional
Reset
Rate
Auto-Manual No
Output Meter No
Set Point - Man. Yes Auto No
Isolation ; input/output Yes
Mounting Rack
Available Contacts (No.of & Hi or Low)
1 hi
1 lo
Voltage Supply 120 ac

FIELD DATA

Signal From SP 209 B
To SP 209 B
Set Point Setting Red.....50%
Green...60%
Prop. Setting
Reset Setting
Rate Setting
Contact: 1st Hi See Remarks
Low
2nd Hi
Low
3rd Hi
Low

Remarks Contacts drive motorized set point in SP 209 B through pulse generating circuit.

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Electronic Trip	6

INDICATING CONTROLLER

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Regulator
Function Set Point Controller
Instrument Type Electronic
Location MCP

Contract No. 69-1
Dwg. Ref. E6
Tag No. SP 209 B
Mfr. F&P
Model No. 53EC3111BB2
Serial No. 6911AO869J23

INSTRUMENT DATA

Input Signal See Remarks
Input Impedance None
Output Signal 4-20 ma
Load Impedance 0-750 Ω
Mode Adjustment:
Proportional
Reset
Rate
Auto-Manual Yes
Output Meter 0-100%
Set Point - Man. Yes Auto Yes
Isolation ; input/output Yes
Mounting Rack
Available Contacts (No.of & Hi or Low)
None

Voltage Supply 120-ac

FIELD DATA

Signal From SP 209 C
To SP209C, TCU & SP209A
Set Point Setting 60%
Prop. Setting
Reset Setting
Rate Setting
Contact: 1st Hi
Low
2nd Hi
Low
3rd Hi
Low

Remarks Output signal proportional to motorized set point driven by SP209C or remotely by computer

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J. F. Lynch	C200	Connecticut St. Regulator Set Point Controller	7

INDICATING CONTROLLER

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Reg.
Function Outfall Gate Controller
Instrument Type Electronic
Location MCP

Contract No. 69-1
Dwg. Ref. E6
Tag No. SP 209 D
Mfr. F&P
Model No. 55EL3111BL2-BBE
Serial No. 6911A0869J32

INSTRUMENT DATA

Input Signal 4-20 ma
Input Impedance 250 Ω
Output Signal Contact
Load Impedance
Mode Adjustment:
Proportional 2-50%
Reset 0-100%
Rate
Auto-Manual yes
Output Meter yes 0-100%
Set Point - Man. yes Auto yes
Isolation ; input/output yes
Mounting Rack
Available Contacts (No.of & Hi or Low)

Hi	1
Lo	1

Voltage Supply 120 ac

FIELD DATA

Signal From SP209A,LX202A
To Outfall Gate
Set Point Setting Auto from SP 209A
Prop. Setting Not Used
Reset Setting Not Used
Rate Setting
Contact: 1st Hi Gate Open
Low Gate Close
2nd Hi
Low
3rd Hi
Low

Remarks Only the contact output is used.
No function for 0-100% scale, prop. or reset.

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J. F. Lynch	C200	Connecticut St. Reg. Outfall Gate Controller	8

INDICATING CONTROLLER

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Reg.
Contract No. 69-1
Dwg. Ref. E6
Function Truck Level Xmitter
Tag. No. LX 202 A
Instrument Type Electronic D/P
Mfr. F&P
Location MCP
Model No. 13D2495RB
Serial No. 6911A0869J10

INSTRUMENT DATA

Range Limits 200" H_2O
Load Impedance
Output Signal 4-20 ma
Max. Overrange
Air Supply
Voltage Supply 48 vdc
Mounting Rack
Calibrated Accuracy 5%
(Zero
(Span

FIELD DATA

Datum Ref. MSL = 100.00 Ft.
Finished Grade Ref.El.
Location of Perm.Ref.
Invert El.of Sewer 99.50
Bubbler Tube El. 100.00
Transmitter Zero Setting
99.00 El. Ref.
Transmitter span Setting 12 Units ft.
or 99.00 to 111.00 Ft.El.
Signal Proportion:
0 ____ to ____ Ft.= 3-15 psi
or ____ to ____ Ft.= 10-50 ma
or 99.00 to 111.00 Ft.= 4-20 ma
Line Pressure ____ psi.
Scale

Remarks

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Reg. Trunk Level Xmitter	9

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Reg.
Function Outfall Gate Position
Instrument Type Electronic R/I
Location MCP

Contract No. 69-1
Dwg. Ref. E6
Tag No. R/I 206B
Mfr. Acromag
Model No. 813-BX-U
Serial No. ADO 609

INSTRUMENT DATA

Input Signal 0-1000 Ω
Set Points
Output Signal 4-20 ma
Set Point Dial Accuracy
Input Impedance
Mounting Side
Voltage Supply 120 vac
Air Supply

FIELD DATA

Signal From POS. X 206 A
To TCU & LR 207
Input Span Setting:
0 to 1000 Ω
Output Span Setting:
4 to 20 ma

Remarks Note: 4 ma equals 0 per cent open.
20 ma equals 100 per cent open.
Gate 84 x 60, Invert 99.50

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F. Lynch	C200	Connecticut St. Regulator Outfall Gate Position	10

CALCULATION SHEET
METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut St. Regulator

Contract No. 69-1

Dwg. Ref. E6

Function Interceptor Level Xmitter

Tag. No. LX 201 A

Instrument Type Electronic D/P

Mfr. F&P

Location MHW 10-137

Model No. 13D2495RB

Serial No. 6911A0869J9

INSTRUMENT DATA

Range Limits 200" H_2O

Load Impedance

Output Signal 4-20 ma

Max. Overrange

Air Supply

Voltage Supply 48 vdc

Mounting Rack

Calibrated Accuracy 5%

Zero

Span

FIELD DATA

Datum Ref. MSL = 100.00 Ft.

Finished Grade Ref.El.

Location of Perm.Ref.

Invert El.of Sewer 94.41

Bubbler Tube El. 94.90

Transmitter Zero Setting

94.90 El. Ref.

Transmitter span Setting 10 Units ft.

or 94.90 to 104.90 Ft.El.

Signal Proportion:

0 ____ to ____ Ft.= 3-15 psi

or ____ to ____ Ft.= 10-50 ma

or 0 to 10 Ft.= 4-20 ma

Line Pressure ____ psi.

Scale

Remarks

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Interceptor Level Xmitter	11

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Station Connecticut Street Regulator
Contract No. 69-1
Dwg. Ref. E-6
Function Reg. Gate Controller
Tag No. LC201C
Instrument Type Electronic Alarm
Mfr. Foxboro
Location MCP
Model No. 63U-BT-OJER-F
Serial No. 2232664

INSTRUMENT DATA

Input Signal 4-20 ma
Input Impedance 250 Ω
Output Signal Contact
Load Impedance
Mode Adjustment:
  Proportional
  Reset
  Rate
Auto-Manual No
Output Meter No
Set Point - Man. Yes Auto No
Isolation ; input/output Yes
Mounting Rack
Available Contacts (No. of & Hi or Low)
Hi 1
Lo 1
Voltage Supply 120-ac

FIELD DATA

Signal From LX 201 A
To Gate Control
Set Point Setting Red...62% Green...58%
Prop. Setting
Reset Setting
Rate Setting
Contact: 1st Hi Gate open
Low Gate close
2nd Hi
Low
3rd Hi
Low

Remarks

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Reg. Gate Controller	12

INDICATING CONTROLLER

CALCULATION SHEET

METROPOLITAN ENGINEERS
SEATTLE, WASHINGTON

DATE: February 28, 1972

Contract No. 69-1

Station Connecticut St. Regulator

Dwg. Ref. E6

Function Reg. Gate Position

Tag No. R/I 205B

Instrument Type Electronic R/I

Mfr. Acromag

Location MCP

Model No. 813-BX-U

Serial No. ADO - 608

INSTRUMENT DATA

Input Signal 0-1000 Ω

Set Points

Output Signal 4-20 ma

Set Point Dial Accuracy

Input Impedance

Mounting Side

Voltage Supply 120 ac

Air Supply

FIELD DATA

Signal From POS-X 205 A

To TCU

Input Span Setting:

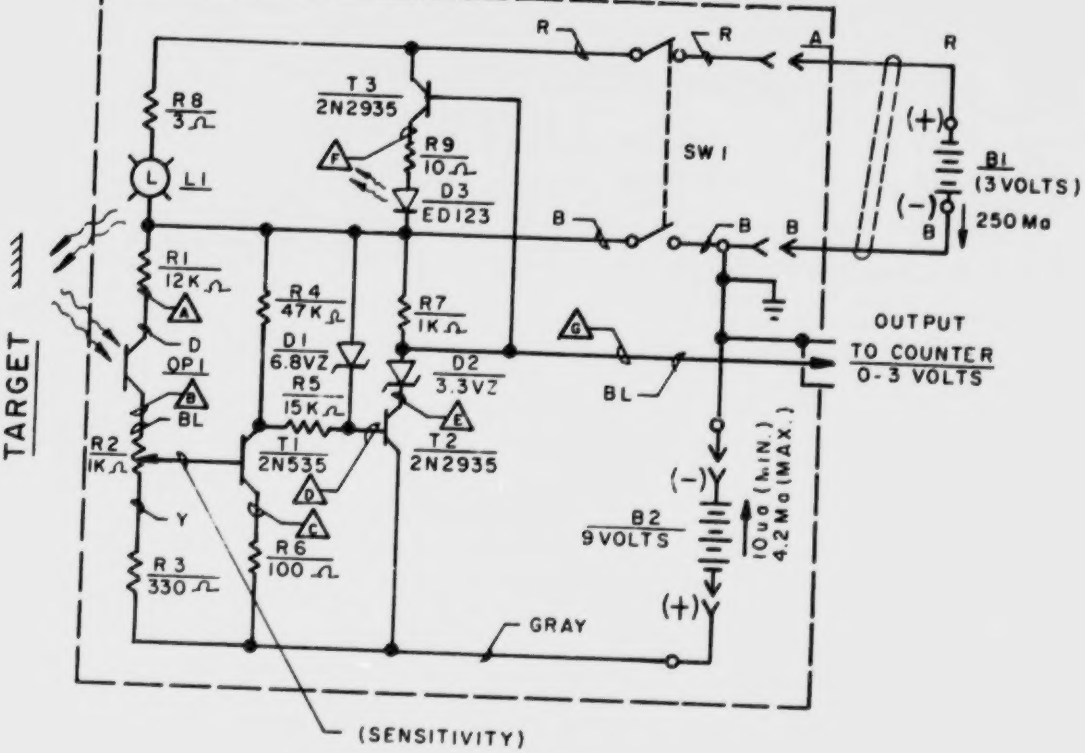
0 to 1000 Ω

Output Span Setting:

4 to 20 ma

Remarks Note: 4 ma equals 0 per cent open
20 ma equals 100 per cent open
Gate 36 x 36, Invert 100.03

DATE	BY	JOB NO.	TITLE	SHT. NO.
2/11/72	J.F.Lynch	C200	Connecticut St. Regulator Reg. Gate Position	13


R
R
A
R
T3
2N2935
R8
3Ω
R9
10Ω
SW1
(+)
B1
(3 VOLTS)
F
L1
D3
ED123
(-)
B
B
B
B
250 Ma
TARGET
R1
12KΩ
A
R4
47KΩ
R7
1KΩ
G
OUTPUT
TO COUNTER
0-3 VOLTS
D
OP1
D1
6.8VZ
D2
3.3VZ
BL
B
R5
15KΩ
BL
E
R2
1KΩ
T1
2N535
T2
2N2935
D
10ua (MIN.)
4.2Ma (MAX.)
(-)
Y
C
B2
9 VOLTS
R3
330Ω
R6
100Ω
(+)
GRAY
(SENSITIVITY)

△ INDICATES VOLTAGE TEST POINT

NOTE: LIGHT EMITTING DIODE, D3, IS A "BITE"
IT INDICATES ALL CONDITIONS FOR ACCURATE OUTPUT ARE CORRECT

DIODE WILL INTERMITTENTLY GLOW RED WHEN:

a. Batteries are correctly connected & sensor is turned on.
b. Sensor is viewing a reflective (WHITE) target on rotating shaft with black background.
c. Optical alignment and distance are correct.
d. Output voltage level is between 2.5 volts & 3 volts.
e. "B1" battery voltage level is between 1.6 volts & 3 volts.
f. "B2" battery voltage level is between 5.6 volts & 9 volts.
g. That there is no failure of components within photo sensor assembly.

BATTERY LIFE:

"B1" battery discharge continuously	to	1.6 volts	70 hrs.
"B2" battery discharge continuously	to	5.6 volts	86 hrs.
"B1" battery discharge 4hr/day	to	1.6 volts	90 hrs.
"B2" battery discharge 4hr/day	to	5.6 volts	120 hrs.

FIGURE C-1
RETROREFLECTIVE PHOTOSENSOR SCHEMATIC

APPENDIX D

APPLICATIONS PROGRAMS
EXECUTIVE SYSTEM PRIORITY ASSIGNMENT

Level	Sublevel	Name	Function
0	0	STNDRIVE	Scan environment protection system Bid clock dependent programs Blink console lights Initiate station contact changes Initiate station demand and command scans Update station data file with new scan data
0	1	CMNHAND	Process station command scans in order to check command progress and complete or abort operations
0	2	CMNDSTRT	Check and initiate station commands
0	3	WTRWRITE	Moves each record of Water Quality data to the Water Quality data file
0	4	FIREMESG	Outputs alarm messages when the environmental protection system detects trouble
0	5-15	UNUSED	
1	0	PROCREGL	Convert and alarm regulator analog data Check and alarm regulator status data
1	1	PROCPUMP	Convert and alarm pump station analog station Check and alarm pump station status data
1	2-15	UNUSED	

Level	Sublevel	Name	Function
2	0	SMTHREGL	Smooth regulator analog data Add calculated flows and new alarms determined by Level 8 to the station data file
2	1	SMTHPUMP	Smooth pump station analog data Add calculated flows and new alarms determined by Level 8 to the station data file Check and alarm pump operation
2	2-15	UNUSED	
3	0	ALRMREGL	Calculate and alarm regulator station rates Add alarm messages to the alarm table Output alarm table overflow messages Freeze station data for hourly log Freeze station data for demand log
3	1	ALRMPUMP	Calculate and alarm pump station rates Add alarm messages to the alarm table Output alarm table overflow messages Freeze station data for hourly log Freeze station data for demand log
3	2	ALRMLOCL	Initiates Station local console command
3	3-15	UNUSED	
4	0	CONSFORM	Output the station data format to the appropriate CRT screen
4	1	CONSUPDT	Update console CRT and lights with new station data
4	2	CONSENTR	Initiate console commands when ENTER button pushed
4	3	CONSCMND	Check and log proposed console commands
4	4	CONSTATN	Process new station push button requests from console
4	5	CONSYSTM	Process new system push button requests from console

Level	Sublevel	Name	Function
4	6	CONSGMNT	Process new segment push button requests from console
4	7	CONSKEYS	Process new digital entry module push button requests from console
4	8	CONSTEST	Output test message events and logging printers
4	9-15	UNUSED	
5	0	RTNRPOLL	Poll Renton Remote Terminal periodically Bid for proper sublevel if command entered by Renton operator Send time of day as computer running indication
5	1	RTNRLOCL	Issue commands to put station or system requested by Renton operator into local control
5	2	RTNRALRM	Display and print at Renton Remote Terminal all alarm messages
5	3	RTNRDISP	Display and optionally print at Renton Remote Terminal the operator requested station's data and alarms and status
5	4	RTNRALRV	Display and optionally print at Renton Remote Terminal the alarms currently active in the operator requested station or system
5	5	RTNRTEST	Send and receive messages to test the operation at the Renton Remote Terminal
5	6	RTNRDATA	Accept data entered by Renton operator and save it on a specified data file
5	7-15	UNUSED	

Level	Sublevel	Name	Function
6	0	WPTRPOLL	Poll West Point Remote Terminal periodically Bid for proper sublevel if command entered by West Point operator Send time of day as computer running indication
6	1	WPTRLOCL	Issue commands to put station or system requested by West Point operator into local control
6	2	WPTRALRM	Display and print at West Point Remote Terminal all alarm messages
6	3	WPTRDISP	Display and optionally print at West Point Remote Terminal the operator requested station's data and alarms and status
6	4	WPTRALRV	Display and optionally print at West Point Remote Terminal the alarms currently active in the operator requested station or system
6	5	WPTREST	Send and receive messages to test the operation at the West Point Remote Terminal
6	6	WPTRDATA	Accept data entered by West Point operator and save it on a specified data file
6	7-15	UNUSED	
7	0	LOGRALRM	Print alarm and normal messages on events printer
7	1	LOGRHOUR	Print an hourly log of the station data on the logging printer
7	2	LOGRHADL	Print an hourly storm log on the logging printer if there has been any rainfall or overflows
7	3	LOGRDMND	Print a log on the logging printer of the station or system data requested by the CATAD console operator

Level	Sublevel	Name	Function
7	4	LOGRDALL	Print a log on the logging printer of the current storm log data for the station or system requested by the CATAD console operator
7	5	LOGRALRV	Print a summary of the current alarms at the station or system requested by the CATAD console operator
7	6	LOGRWQAL	Print an hourly log on the logging printer of the data collected by the Water Quality Monitoring System
7	7-15	UNUSED	
8	0	FLOWREGL	Calculate Regulator flow, interceptor flow, overflow Accumulate overflow volumes Calculate station maximum flow Bid Level 8 sublevels 2, 4,6
8	1	FLOWPUMP	Calculate pump discharge, force main flow and bypass flow Accumulate bypass volume Calculate station maximum flow Bid Level 8 sublevels 3, 5, 7
8	2	STORREGL	Calculate trunk inflow, storage rate
8	3	STORPUMP	Calculate inflow, storage rate
8	4	AUTOREGL	Calculate safe diverted flow and set-point. In storage mode, calculate optimal diverted flow from rule curve Bid Level 8 sublevel 6
8	5	AUTOPUMP	Calculate maximum safe discharge or maximum safe setpoint Bid Level 8 sublevel 7
8	6	SUPRREGL	Calculate necessary regulator position to give flow requested by operator or AUTOREGL

Level	Sublevel	Name	Function
8	7	SUPRPUMP	Calculate safe setpoint to give station discharge required by AUTOPUMP or operator
8	8	RAINUPDT	Saves rainfall data from Level 3 on rain data file on RAD
8	9-15	UNUSED	
9	0	BGNDCKPT	Checkpoint background before running other Level 9 sublevels
9	1-14	UNUSED	
9	15	BGNDREST	Restart background after completion of all other Level 9 sublevels

APPENDIX E

FORCE MAIN CALIBRATION CURVES

Figure E-1: Kenmore Pump Station, Pump #3

Figure E-2: Kenmore Pump Station, Combined

Figure E-3: Matthews Park Pump Station

Figure E-4: Interbay Pump Station, East

Figure E-5: Interbay Pump Station, Combined

Figure E-6: Interbay Pump Station, West

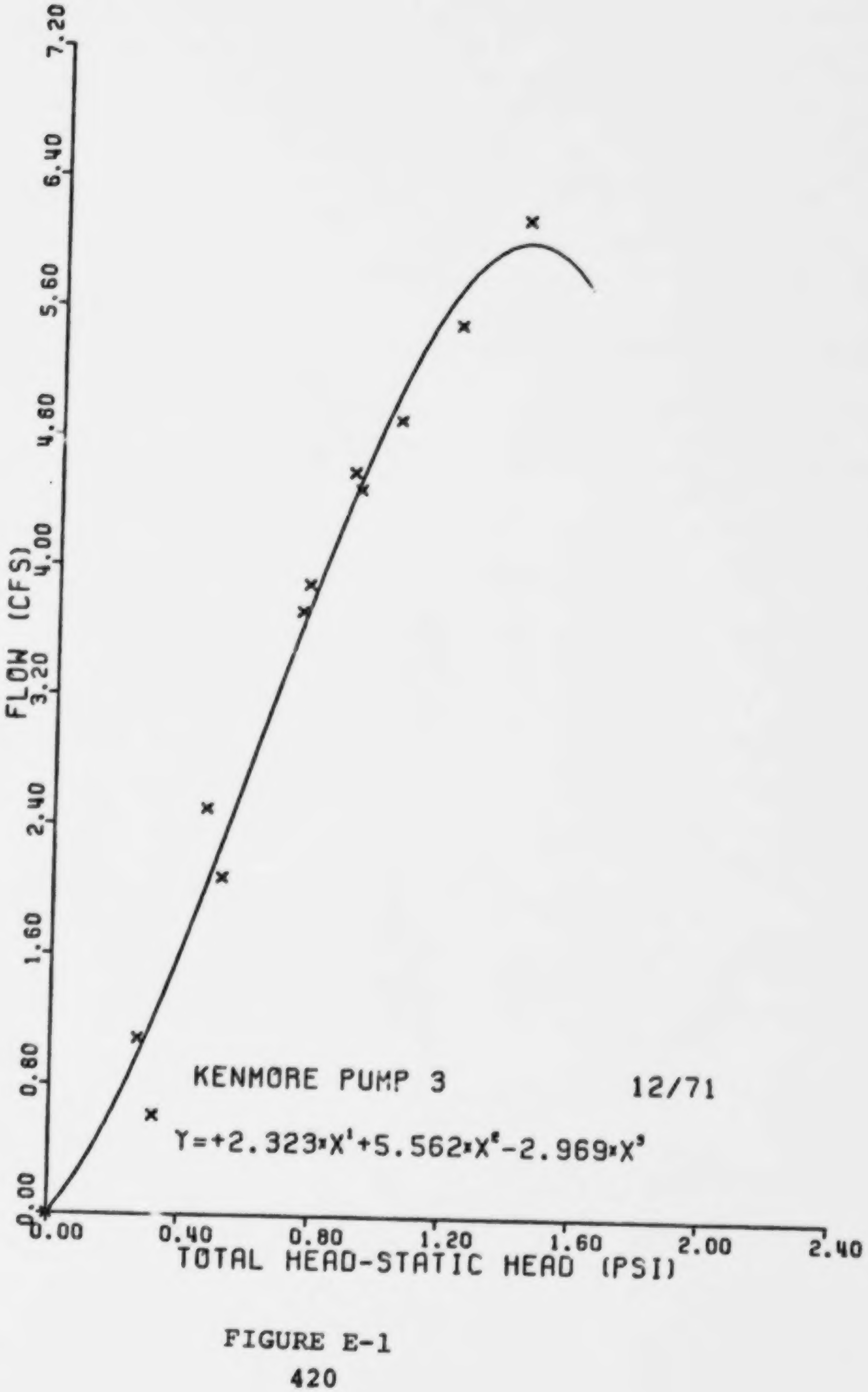

FLOW (CFS)
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
0.00
0.40
0.80
1.20
1.60
2.00
2.40
TOTAL HEAD-STATIC HEAD (PSI)
KENMORE PUMP 3
12/71
Y=+2.323*X¹+5.562*X²-2.969*X³

FIGURE E-1

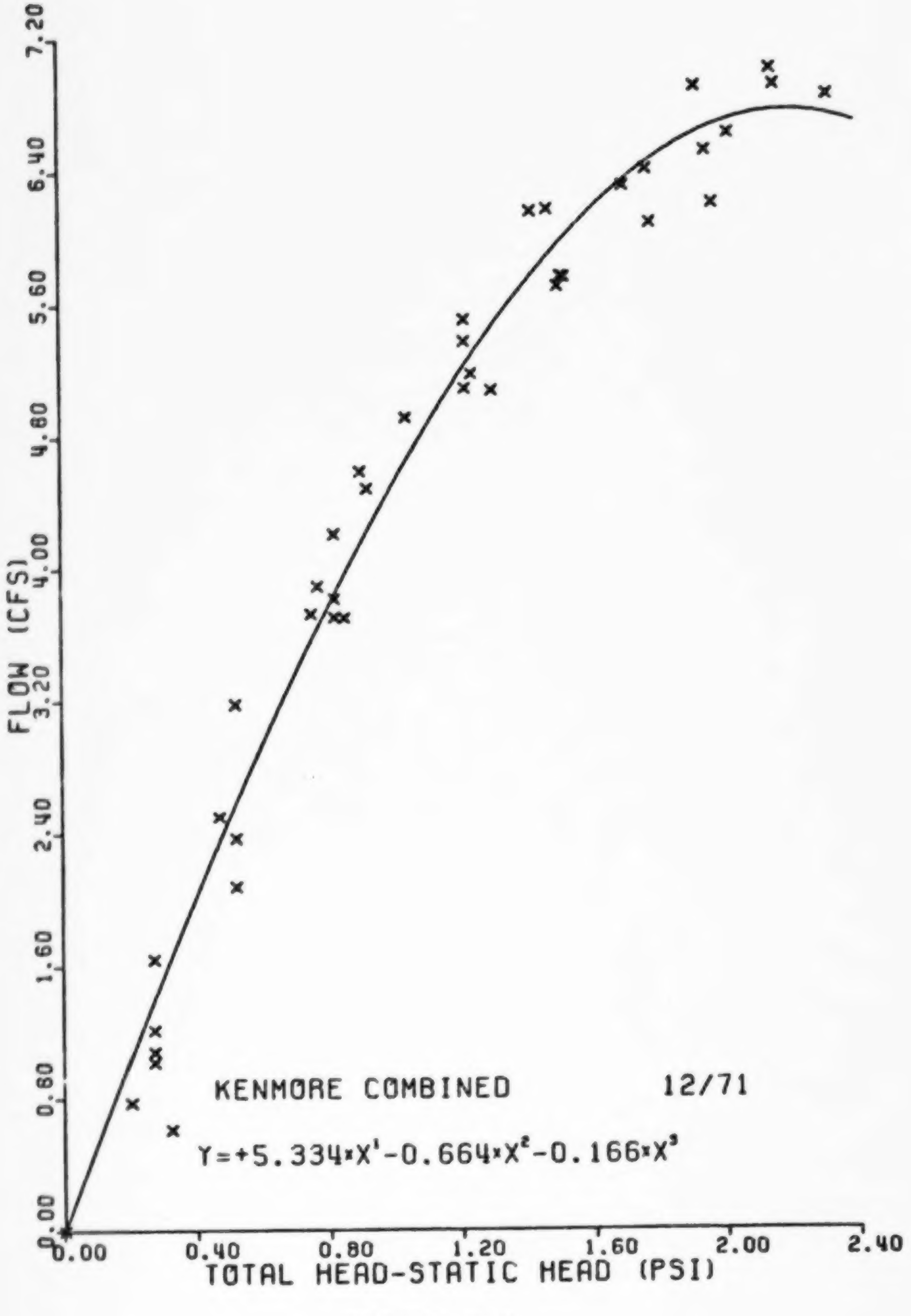

KENMORE COMBINED 12/71
Y=+5.334×X¹-0.664×X²-0.166×X³
FLOW (CFS)
0.00
0.80
1.60
2.40
3.20
4.00
4.80
5.60
6.40
7.20
TOTAL HEAD-STATIC HEAD (PSI)
0.00
0.40
0.80
1.20
1.60
2.00
2.40

FIGURE E-2

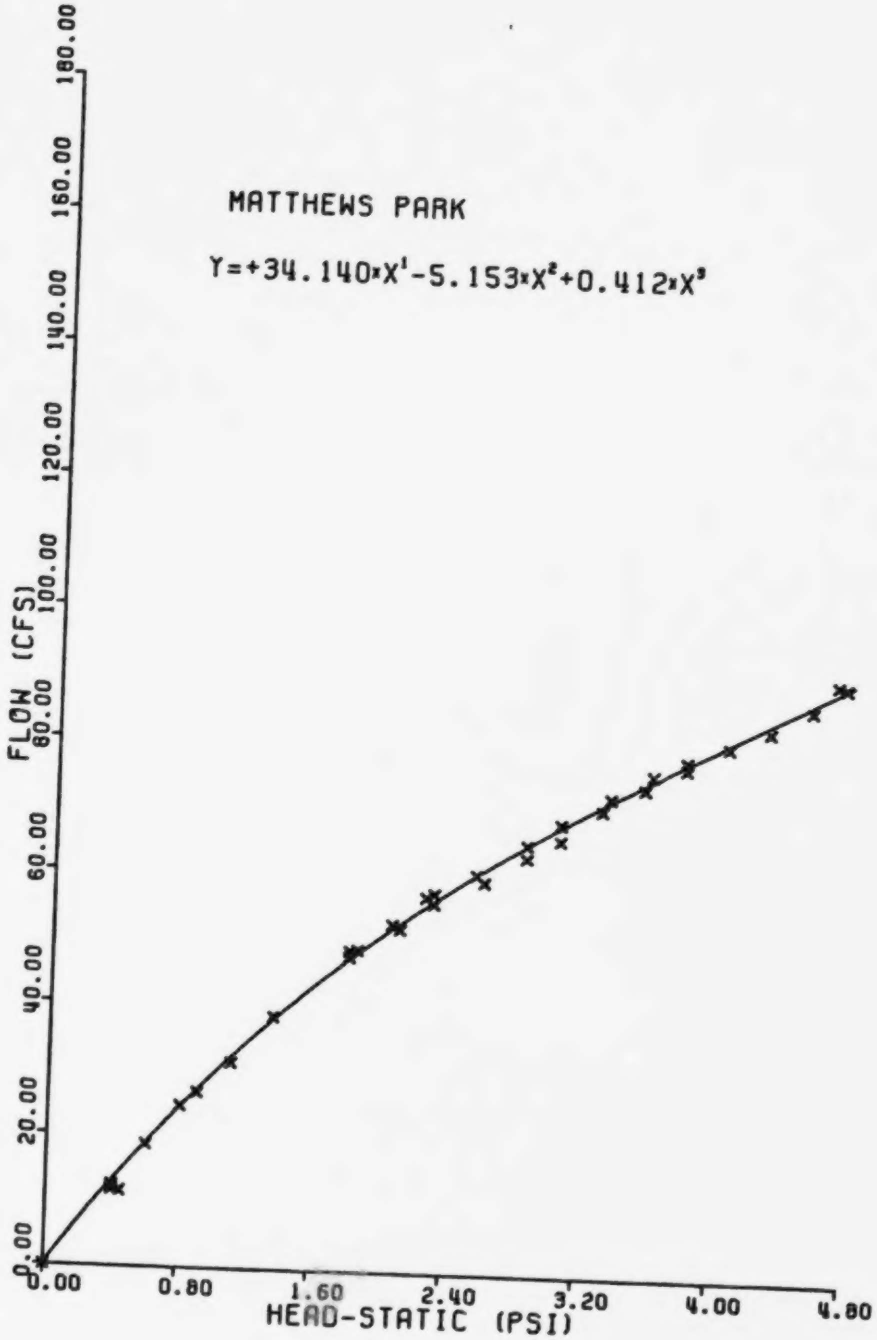

MATTHEWS PARK
Y=+34.140*X¹-5.153*X²+0.412*X³
FLOW (CFS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
HEAD-STATIC (PSI)
0.00
0.80
1.60
2.40
3.20
4.00
4.80

FIGURE E-3

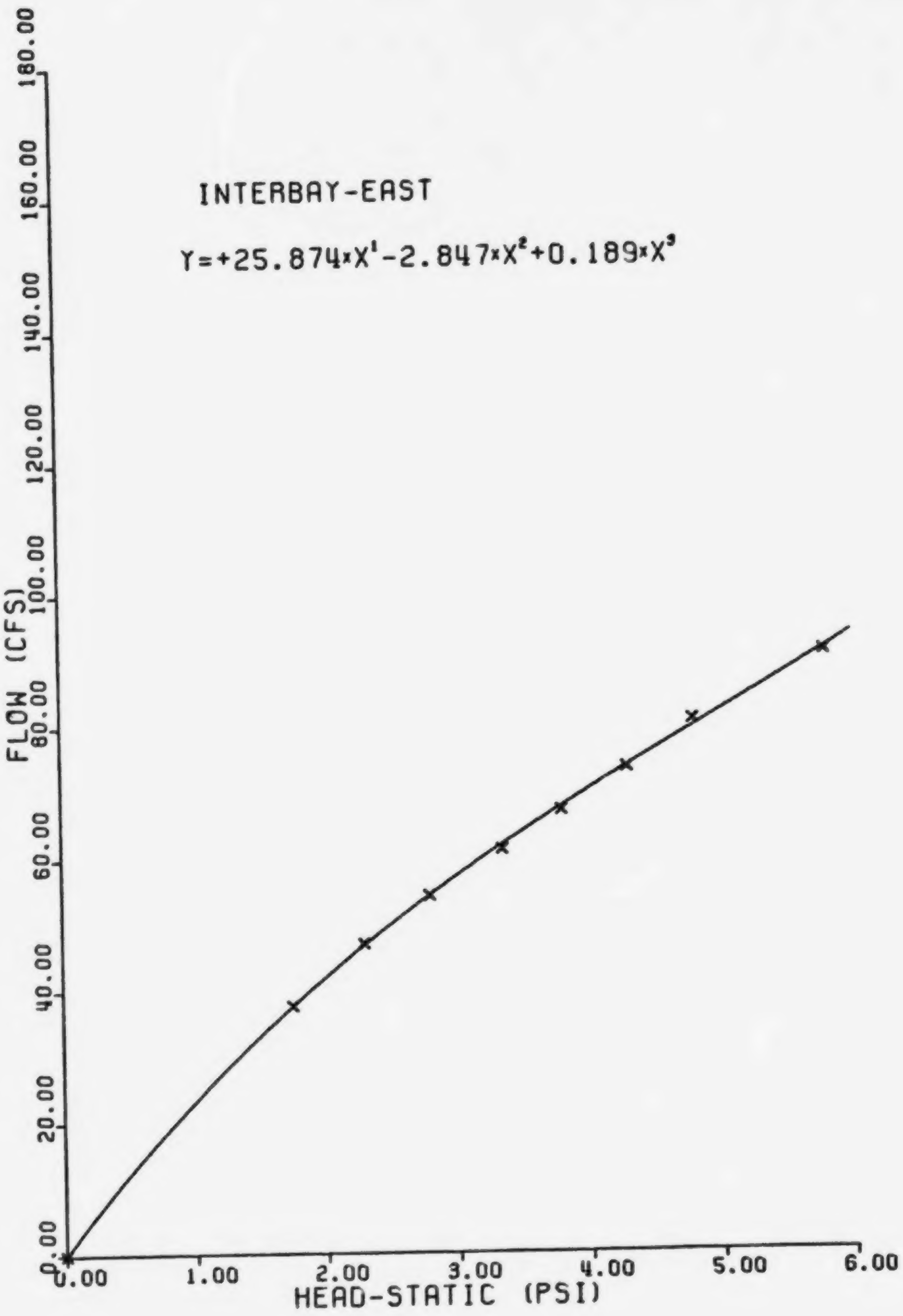

INTERBAY-EAST
Y=+25.874×X¹-2.847×X²+0.189×X³
FLOW (CFS)
HEAD-STATIC (PSI)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00

FIGURE E-4

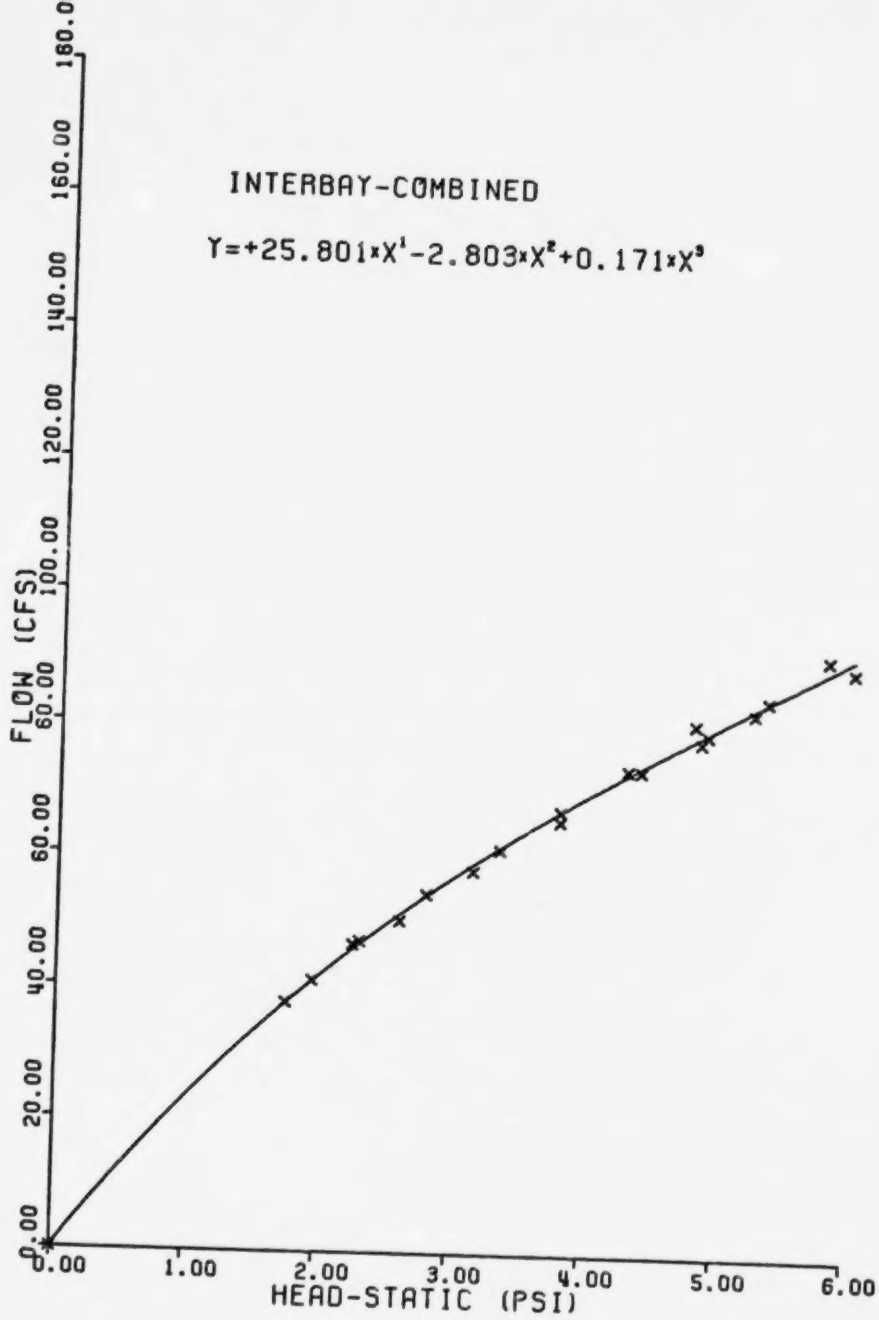

INTERBAY-COMBINED
Y=+25.801×X¹-2.803×X²+0.171×X³
FLOW (CFS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
HEAD-STATIC (PSI)
0.00
1.00
2.00
3.00
4.00
5.00
6.00

FIGURE E-5

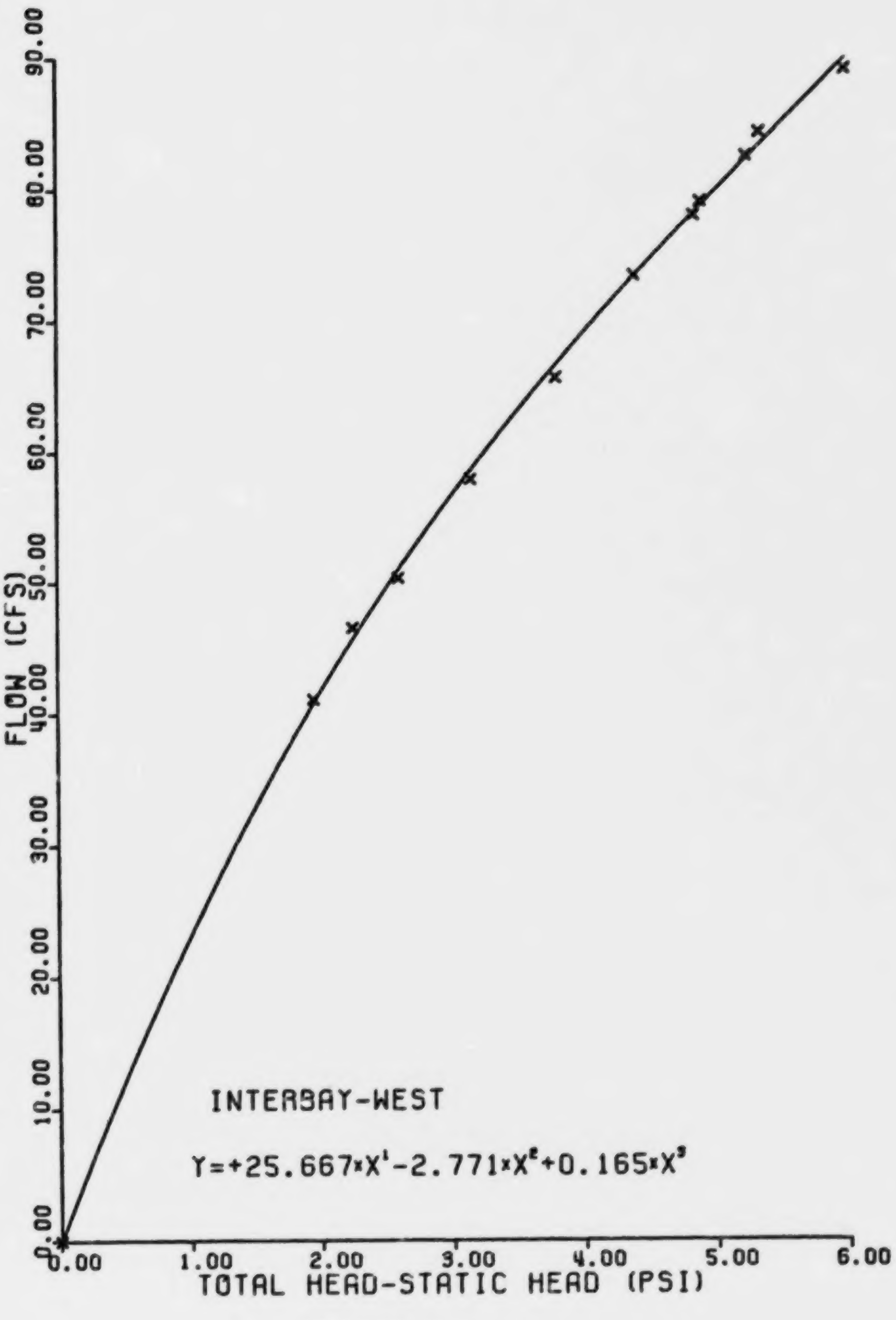

FLOW (CFS)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
TOTAL HEAD-STATIC HEAD (PSI)
INTERBAY-WEST
$Y=+25.667 \times X^1-2.771 \times X^2+0.165 \times X^3$

FIGURE E-6

REGULATOR SAMPLER EXPERIENCE

Allocation of manhours to the study varied both during different seasons and also according to the individuals involved. During the periods of frequent overflows, the water quality technician assigned to CATAD worked as follows: sample collection, 40 percent; lab analysis, 55 percent; data handling, 5 percent. Conflicting duties at these times were kept to a minimum. When rainfall became infrequent and the number of overflows low, time was spent in the following way: field work, 10 percent; lab work, 5-10 percent; data handling, 50 percent; other Metro water quality studies, 30-35 percent. Other lab technicians involved contributed 6-8 percent of their time for sampling during the summer periods. The instrument technicians from the maintenance division used 4.5 percent of their time on CATAD related duties. In the winter this involved 9-14 percent of his time repairing samplers. Maintenance crews assigned to routine maintenance and inspection work spent 1 percent of their time on CATAD.

During the sampling study, a great deal of data was gathered and considerable experience garnered. Some of this data later proved to be unsuitable for use in the evaluation of the project. Failure of the samplers proved to be the major cause of invalid data collection. All the samplers had problems which were often unique to the individual sampling device. The following is a breakdown of major problems: Line plugged by debris or smashed by closing gates, 36 percent; pump breakdown, 21 percent; programmer malfunction, 21 percent; refrigeration failure, 15 percent; fuse blowing, 10 percent; sampler counter malfunction, 5 percent.

The most vexing problem experienced was recorder pen failure, particularly during critical overflow periods. Ninety-five percent of recorder problems reported dealt with this problem. Failure of any one of three level recording pens prevented reliable computation of flow information. The loss of flow information prevented calculation of loading figures and caused efforts in sample collection and analysis to be of limited value. Continuous checking proved to be the only way to keep this problem at a reasonable level. Transferring coordinates from strip charts to computer cards was excessively time consuming. Loss of flow data, either through pen failure or misplacement of charts, has been the biggest limiting factor in evaluation of sampling data.

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Continuous checking and maintenance appears to be the only remedy to the sampler and recorder problems. The priority in work scheduling was not sufficiently high enough to prevent the downtime experienced in spite of instrument technicians available. If practical, a central location for logging the data would have simplified both surveillance and maintenance.

During the course of this study, few major problems with lab analysis became evident. Unfortunately, the Technicon Auto-Analyzer was not of great value in sample analysis. To be really effective, a multi-channel installation would have been needed. Experience showed that it was faster to run most of the tests manually than to set up the single-channel Auto Analyzer for each test. It did prove valuable to the lab in general. Much needed space and equipment was liberated when the Analyzer performed one of the routine quality analysis, the test for nitrate nitrogen.

The biggest problem encountered with the sequential samplers was in the method of timing sample collection. The programmer disks often were not turning at the correct rate because linkup was provided by friction between a groove and rubber O-ring. Slippage could have been avoided entirely had the disk been gear driven. The method of changing sample bottles was time consuming and sometimes hazardous. The brittle glass bottles occasionally broke off at the neck in the sampler, leaving jagged debris in the confined area of the refrigerator. Coating the bottle threads with silicone stopcock grease partly alleviated this problem and also improved sealing. The composite sampler mechanism was more dependable than the sequential sampling units. A minor inconvenience, peculiar to this type of sampler, was the necessity of prompt sample pickups. In the event of two storms close together, sample mixing of two overflows could occur.

The samplers were a prototype and suffered from lack of refinement in design and workmanship. For example, the pumps used (being oil-less) were not designed to operate in a damp environment. Due to design shortcomings, one of the main starting switches would initiate the sampling cycle after power failures or emergency generator tests. The refrigeration units would not maintain a constant temperature because of control by an external thermostat. Because the units were manufactured in Europe, parts were difficult to obtain. After the initial problems were corrected, the samplers functioned fairly reliably, considering the conditions under which they were used.

The large number of samples that needed immediate attention caused congestion at certain lab equipment used by other projects; the spectrophotometer in particular. This problem was solved when another spectrophotometer was purchased.

Problems also occurred with data handling. Routine logging of data was put off during sample collection and laboratory analysis and became harder to bring up to date later. Although the heavy work load necessitated postponement of some computation and logging, more current updating of the data would have been preferred. This would have assisted in pinpointing possible deficiencies. A system of monthly reports to the supervisor in the form of a computer printout and storage of data on easily accessible tapes would have done much to eliminate the problem. The more detailed evaluation could still have been reserved for slack sampling periods. When undertaking a sampling program of this type, there are three points to keep in mind:

1. All those involved in such a study should have an understanding of the aims and priorities of his job and the project as a whole.
2. Consistency in the laboratory and field sampling must be carefully watched and maintained by all participants.
3. Any changes in techniques or methods should be correlated directly to the previous procedures before any changeover is approved.

During the program, technicians and supervisors should have a definite idea of the progress of the data gathering and how it will relate to the stated aims of the study. While equipment problems can be minimized with adequate experience and backup, one must continually work on project coordination and direction of the principals involved.

ROUTINE MONITOR CLEANING PROCEDURE

Winter - once per week

Rest of Year -- twice per week

1. Check float and hose for obvious problems.
2. Upon entering monitor station, check pump and meters, analyzer dials and recorder for failures.
    a. If pump is found off or plugged (amperage O.K. but no flow), call Renton Maintenance and report it (BA6-8294).
    b. If recorder, analyzer or probe (except DO) problem found, notify West Point Instrument Lab (Dick Trask, AT4-6336).
3. Clean probes, flow cells, reservoir-to-cell tubes, and note on check sheet. Clean reservoirs if necessary; once per month is probably sufficient.
4. Make recorder check and note conditions on check sheet.
5. Draw dissolved oxygen sample(s) from spigot(s), fix with dry reagents provided and titrate. If necessary, adjust value for conductivity. Compare the titrated value with the analyzer reading and adjust analyzer if necessary (full-scale set screw). Record any adjustment made as well as other DO check information on appropriate part of check sheet. If no adjustment ("trim") is available, or if analyzer is off by more than 0.5 mg/l, the DO probe probably needs to be replaced.
6. Temperature, pH and conductivity calibration checks will be made on a monthly basis and recorded on check sheet. Other than minor adjustments (+ or - a few units) should be handled by the Instrument Technician.
7. Record on check sheet all information about cleaning done, analyzer or probe changes, supplies needed, telemetry checks, and date and time.
8. Telemeter check for each station once per week. Request zero and span adjustments (from Disk Trask) when drift is sufficiently large.

9. Record briefly in log book and on recorder chart the time of visit, adjustments made, any problem, and initials.

10. Upon leaving, be sure recorder is operating correctly, thermostat is set at 60°, lights are out and door is locked.

APPENDIX G

CONTROL SYSTEM DESCRIPTION

DETAILED REGULATOR AND OUTFALL CONTROL SYSTEM

The following explanation of regulator and outfall gate controls refers to Figure G-1. The regulator control system provides a milliampere-transmitted signal reflecting the measured (bubbled) interceptor level for local indication and for transmission to the TCU A/D converter. The pneumatic bubbler level signal is also applied to the bellows of the regulator gate controller instrument which has manually adjusted high and low setpoint contacts. Raise and lower contactors of the gate motor starter are controlled by these contact closures when the central computer has released command of the regulator, by de-energizing the computer-local (CLR) relay. When the central computer command picks up the CLR relay, only direct contact closure of the regulator open (RO) relay or the regulator close (RC) relay in the TCU can cause gate movement. The same system controls the outfall gate in the four stations which do not have usable trunk sewer storage.

The principal control elements of the electronic outfall gate control system are the manual controller and the referenced setpoint unit. The manual controller is provided with a step-driven setpoint which has a range of about 1,000 steps. The reference setpoint electronic monitor unit has high and low contacts and an adjustable setpoint. The monitor unit compares the electronic output signal of the manual controller with its own setpoint. If the two values differ by more than the preset instrument dead band, then either the high or low contacts of the monitor will close, completing the circuit through one pulse generator unit to the manual controller setpoint. The setpoint moves until the manual controller output and the monitor's setpoint agree, providing a constant trunk level system setpoint, which is affected only by a tidal level within six inches of the storage level. In this case, the high signal selector chooses the tidal level and raises the setpoint of the gate controller instrument.

Under central computer command of the outfall gate, relay CLR picks up, removing pulse source 1 and the reference setpoint monitor from the system. Pulse source 2 (which may be set at a different rate than pulse source 1) is connected to the manual controller circuitry. A central computer gate operation command picks up the outfall open (OO) relay or the outfall close (OC) relay in the TCU, causing the manual controller setpoint to move at the preset pulsing rate. Manual controller output feeds directly through I/I isolator and high selector to the gate controller. In case of signal loss, the manual controller setpoint and the reference setpoint may disagree. The manual controller setpoint moves to balance the condi-

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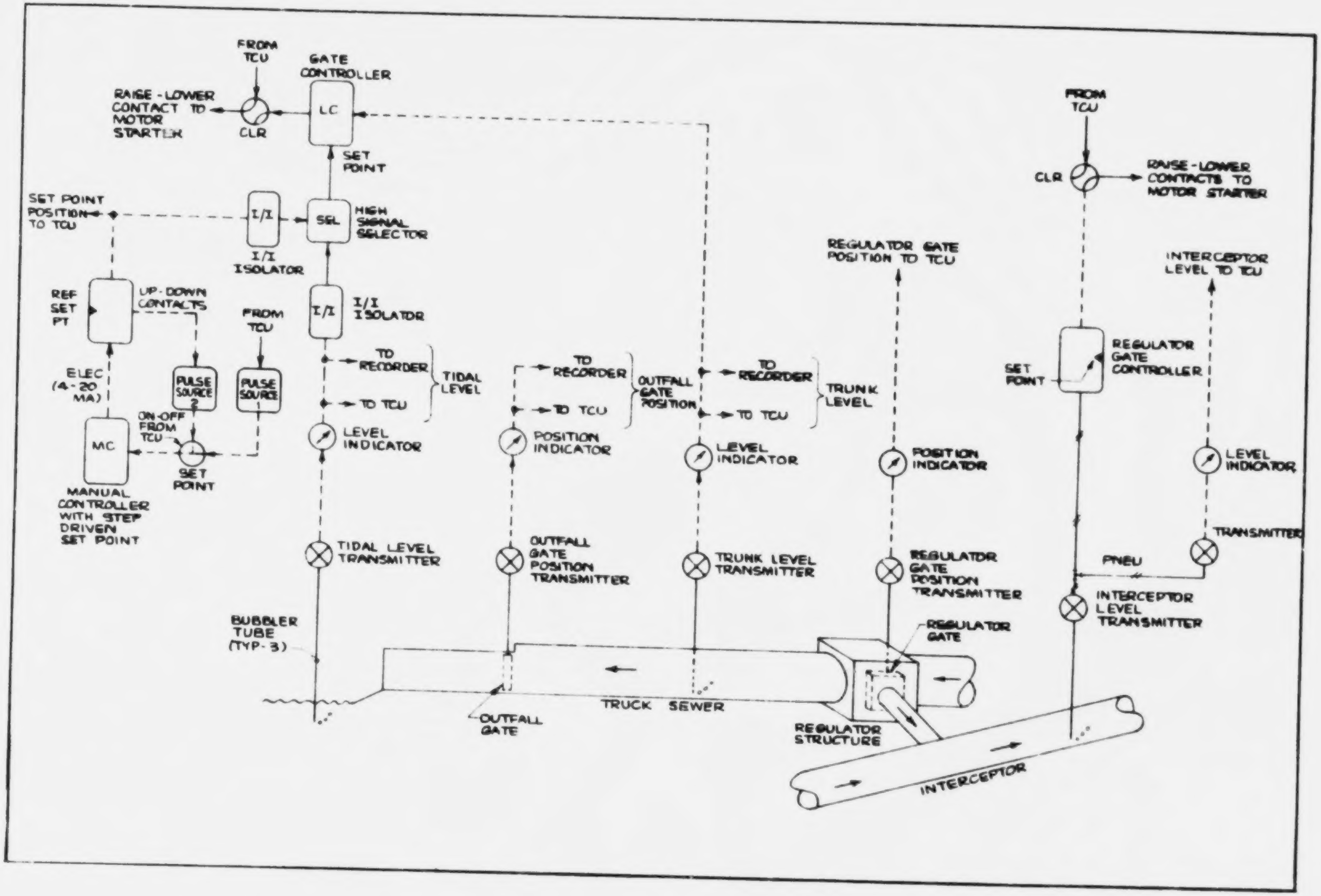

FROM TCU
GATE CONTROLLER
RAISE-LOWER CONTACT TO MOTOR STARTER
CLR
LC
SET POINT
SET POINT POSITION TO TCU
I/I
SEL
HIGH SIGNAL SELECTOR
I/I ISOLATOR
REF SET PT
UP-DOWN CONTACTS
FROM TCU
I/I
I/I ISOLATOR
ELEC (4-20 MA)
PULSE SOURCE 2
PULSE SOURCE
ON-OFF FROM TCU
MC
SET POINT
MANUAL CONTROLLER WITH STEP DRIVEN SET POINT
TO RECORDER
TO TCU
TIDAL LEVEL
LEVEL INDICATOR
TIDAL LEVEL TRANSMITTER
BUBBLER TUBE (TYP-3)
TO RECORDER
TO TCU
OUTFALL GATE POSITION
POSITION INDICATOR
OUTFALL GATE POSITION TRANSMITTER
OUTFALL GATE
TO RECORDER
TO TCU
TRUNK LEVEL
LEVEL INDICATOR
TRUNK LEVEL TRANSMITTER
TRUCK SEWER
REGULATOR GATE POSITION TO TCU
POSITION INDICATOR
REGULATOR GATE POSITION TRANSMITTER
REGULATOR GATE
REGULATOR STRUCTURE
INTERCEPTOR
FROM TCU
CLR
RAISE-LOWER CONTACTS TO MOTOR STARTER
INTERCEPTOR LEVEL TO TCU
SET POINT
REGULATOR GATE CONTROLLER
LEVEL INDICATOR
TRANSMITTER
PNEU
INTERCEPTOR LEVEL TRANSMITTER

FIGURE G-1

REGULATOR STATION CONTROL SCHEMATIC

tion, opening or closing the gate (if required). Two pulse generators were provided due to the design requirement that system response speed for computer command be greater than the speed of ramping back to fixed setpoint. Ramping speed is determined set by monitoring after installation.

PUMPING STATION CONTROLS

Although the various pumping station control systems differed greatly in detail and principle of control, level measurement using a bubbler in the wet well was common to all stations.

Facility analysis and a study of the wide control variations indicated that the simplest and most straight-forward central control procedure would leave the individual control systems in tact and insert a substitute signal to replace the actual level measurement. Under this system, a computer link failure could leave a station with an abnormally high wet well level for some particular inflow rate; resulting in additional pumping unit being unnecessarily brought on the line. To prevent this, a ramping system similar to that described for control of the outfall gates was designed (Figure G-2). This system gradually lowers the control point to meet the true momentary wet well level. It produces a gradual pump speed change rather than an instantaneous reaction in case computer control is lost.

DETAILED PUMPING STATION CONTROL SYSTEM

Pumping stations designated for central computer system control were provided with ramping instrumentation systems. Stations not designated for central control were provided with monitoring instrumentation only.

Most small pumping stations were provided with direct operating level transmitter bellows. The transmitter was usually a Foxboro large case contact controller with an auxiliary electronic transmitter to provide the analog signal for pumping speed control. It was necessary to add instrumentation to this system, but it was deemed impractical to work with the low air pressures applied to the contact controller bellows directly from the bubbler reaction system. A pneumatic differential pressure transmitter measures bubbler reaction pressure and converts it to the normal 3-15 psig control air pressure. Local control feeds this pressure through a solenoid valve (SV-1) to the original electric contact control instrument (modified by addition of a 3-15 psi range receiver bellows).

The basic local control system was unchanged in principle but made subject to remote computer control. The electric contact controller proportional level signal is applied to the pump speed

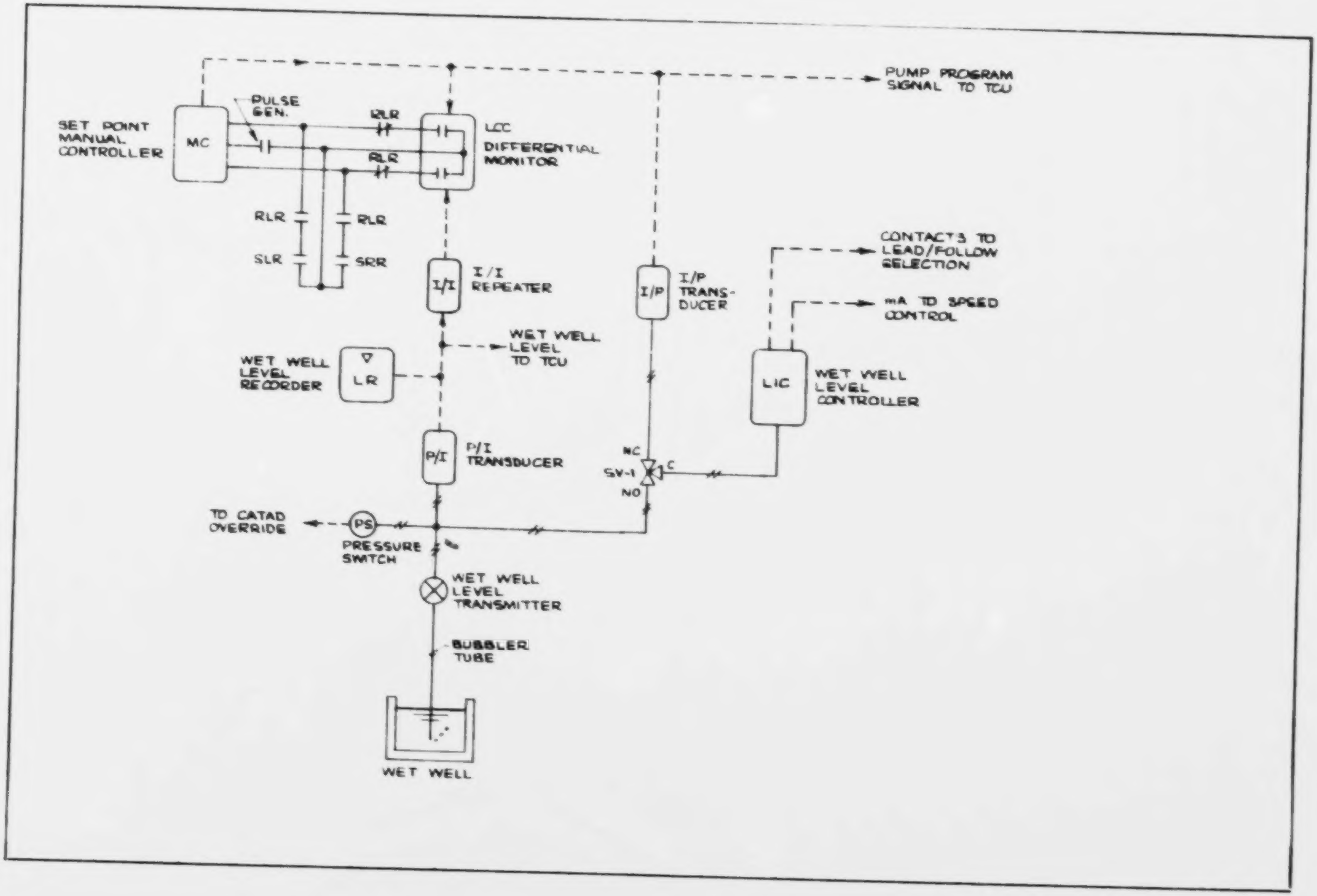

PUMP PROGRAM SIGNAL TO TCU
SET POINT MANUAL CONTROLLER
MC
PULSE GEN.
RLR
RLR
LCC
DIFFERENTIAL MONITOR
RLR
SLR
RLR
SRR
I/I
I/I REPEATER
I/P
I/P TRANS-DUCER
CONTACTS TO LEAD/FOLLOW SELECTION
mA TO SPEED CONTROL
WET WELL LEVEL TO TCU
WET WELL LEVEL RECORDER
LR
LIC
WET WELL LEVEL CONTROLLER
P/I
P/I TRANSDUCER
NC
SV-1
C
NO
TO CATAD OVERRIDE
PS
PRESSURE SWITCH
WET WELL LEVEL TRANSMITTER
BUBBLER TUBE
WET WELL

FIGURE G-2

PUMPING STATION CONTROL SCHEMATIC

control system as the measured variable. Level changes result in pump speed changes so that pumping capacity always matches the station inflow.

A pneumatic-to-current converter (P/I) and a pressure switch were tapped off the pneumatic output of the wet well level transmitter. The pressure switch provides a safety measure to drop out computer control (revert to local control) by de-energizing solenoid valve SV-1, in case extremely high wet well level conditions.

The output of the P/I converter provides the wet well level for analog signal CATAD TCU monitoring and is also fed to an electronic monitoring unit. This unit provides the permissive contacts that control setpoint movement on a motorized setpoint manual control station identical to that in the outfall gate control system. A pulse generator provides a continuous train of contact closures at a preset rate to effect setpoint change at the desired rate. The manual controller output is fed to the electronic monitor unit for reference and to a current-to-pneumatic (I/P) converter for control purposes. CATAD monitors the value of this analog signal via the TCU. The pneumatic output of the I/P converter is fed to the NC tap of solenoid valve SV-1 which is always energized after CATAD has been given control of the station by the wet well selector switch (WWSS).

The electronic monitor unit differs from the outfall gate controls in that it is a pure differential unit with no fixed or manually adjusted setpoint. If the two input signals are balanced, within a small dead band, both output contacts are open. If one signal is higher, a contact pair closes; and if the other signal is higher, the second contact pair closes. Any differential between the manual controller output and the true wet well level causes the manual controller setpoint to move at a rate determined by the pulse generator and in a direction to produce corrective action. When the signals are balanced, the manual controller responds to the wet well signal and moves with it.

Under computer control the TCU CLR relay is picked up and the level raise or lower signal is given by command contact closures. The controller setpoint moves up or down in response to the pulse generator output. Output current change directly affects the level contact controller and thence the pump speed. The wet well level may or may not change depending upon conditions, but the level signal from the bubbler/transmitter system is continually fed to the differential monitor and the monitor contacts are available for control if the computer link is lost.

If the system is locked out by high level actuation of the pressure switch, the full pneumatic control signal is applied directly to the contact controller and whatever additional pumping capacity is programmed to match this level is brought in to use. Most stations provide a further stage of backup control derived directly from an independent float switch in the wet well which activates the standby pumping unit. Most stations have one pump in standby service which is not programmed to operate directly in the lead-follow system and is available for such backup operation.

APPENDIX H

PUMP STATION FORCE MAIN CALIBRATIONS

Table H-1: Force Main Calibration Equipment

Figure H-1: Force Main Calibration Setup

Figure H-2: Salinity-Time Graph

Figure H-3: Kenmore Force Main Calibration

Table H-2: Station Discharge Equations

Table H-3: Darcy Equation Summary

Figure H-4: Darcy "F" Values

Figure H-5: Force Main Pressure Transmitter Installation

Table H-4: Force Main Calibration Equipment: Components and Characteristics

Figure H-6: Typical Force Main Calibration Mask

APPENDIX H

PUMP STATION FORCE MAIN CALIBRATIONS

Field calibration instrumentation is listed in Table H-1.

Table H-1. FORCE MAIN CALIBRATION EQUIPMENT

Component	Characteristics
Recorder	Esterline Angus, 2-channel, Model 1102E, complete with AZAS Range 0-1 mv and 0-200 v d-c.
Pressure Transducer	Rosemont Model 1101, Range 0-100 psig, Accuracy 0.15% of full scale. Output 0-5 v d-c.
Pressure Gauges 1 each of 30, 60 and 100 psi range.	Ametek/U.S. Gauge, Model 1972, 4½" diameter, 316 ss bourdon tube furnished with certified calibration chart.
Rotometer	Differential Pressure, Fischer and Porter Model No. 10A3135, 3.3 GPH, 200 psig max.
Salt Injector	Metro maintenance constructed
Salinity Probe	Metro maintenance constructed
Salinity Meter	Low cost multimeter

The pressure transducer has an accuracy of 0.15 percent over its total range and provides an output of 0 to 5 volts d-c proportional to the range of the instrument. The recorder can spread any portion of the 0 to 5-volt signal into the full range of the chart. In this application, a 20-psi input range spread across the full 10-inch span of the chart provides resolution of the least marked chart graduation of 0.2 psi and approximations of 0.02 psi.

The rotometer provides a small (1.5gph) fresh water flow to continually flush the pressure-sensing equipment. Two salt injectors were job constructed; one of two-inch steel pipe for low flow stations, and the second of four-inch steel pipe for large flow stations. Outlet connections consist of a 1-inch steel pipe which is threaded into either the pump suction or discharge piping, and a quarter-turn ball valve for controlling salt release. A pressure fitting in the salt injector cap permits injection of station air to blow salt out of the tube. The salinity probe is a wooden pole with two copper strips located on the base which are exposed to the sewage. Wiring leads up the probe to the salinity meter, a low cost millimeter connected in series with a 6-volt d-c battery.

A typical calibration setup is shown in Figure H-1. The salt injector is preferably connected to the pump suction, but can be connected to the pump discharge when testing shows that salt injection into the suction causes pump air binding, a frequent occurance on smaller pumps. Salt injection into the pump suction is preferable because less air pressure is required to discharge the salt. The pressure transducer and associated equipment are connected to the force main pressure tap. The recorder is set up in the motor control room so the pump station operator can watch the events taking place and increase or decrease the pressure. The salinity probe and indicator are located at the end of the force main where it discharges into the interceptor. Stations within the Municipality's systems are all automatic and generally do not require the services of a manned operation. However, for this testing, all pumping was controlled by a pump station operator assigned by the Municipality to the force main calibration crew. Pump control rooms are generally located above grade while most of the force main pressure taps and motors are located in the structure below grade. To begin a calibration run, the station is shut down, all pumping shut off, and the wet well levels allowed to build to the highest safe levels which can be maintained in the system in order to provide sufficient liquid for the calibration run. The force main static pressure is checked against the as-built drawings to verify the relative difference in elevation between the force main discharge and the pressure tap. When sufficient storage is obtained, the pumps are started, and the pressure brought up to a constant level. The recorder located next to the operator in the control room provides the operator with the visual indication of trends of increasing or decreasing pressure. Pressure is maintained at a constant level throughout a given run. Background milliamperage is checked at the salinity probe. When all values are in order, the cock on the salt injector (previously charged with salt and compressed air) is opened. The salt is blown into the pump and forced into the force main. Salt wedge travel time in the force main is monitored with two stop watches which are started together and checked for time correspondence approximately every hour. Time is maintained to the nearest second. A typical salinity increase is noted in Figure H-2 which shows the salt wedge passing the salinity probe at the end of the force main. Radio communication is maintained with personnel at the probe station. A typical station force main calibration takes approximately three days. Salt injection is approximately one pound for each million gallons per day of flow.

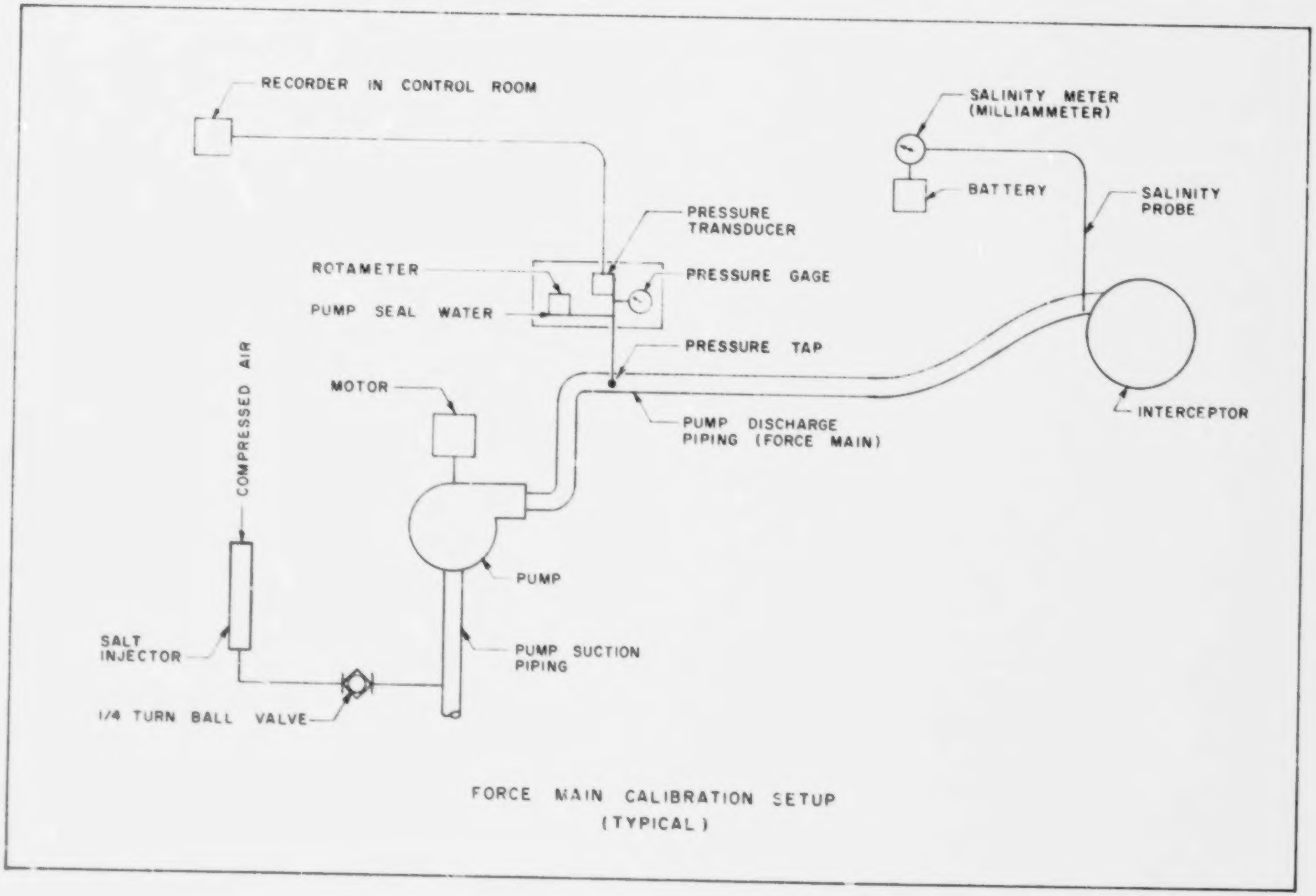

RECORDER IN CONTROL ROOM
SALINITY METER (MILLIAMMETER)
BATTERY
SALINITY PROBE
PRESSURE TRANSDUCER
ROTAMETER
PRESSURE GAGE
PUMP SEAL WATER
PRESSURE TAP
COMPRESSED AIR
MOTOR
PUMP DISCHARGE PIPING (FORCE MAIN)
INTERCEPTOR
PUMP
SALT INJECTOR
PUMP SUCTION PIPING
1/4 TURN BALL VALVE
FORCE MAIN CALIBRATION SETUP (TYPICAL)

FIGURE H-1

FORCE MAIN CALIBRATION SETUP

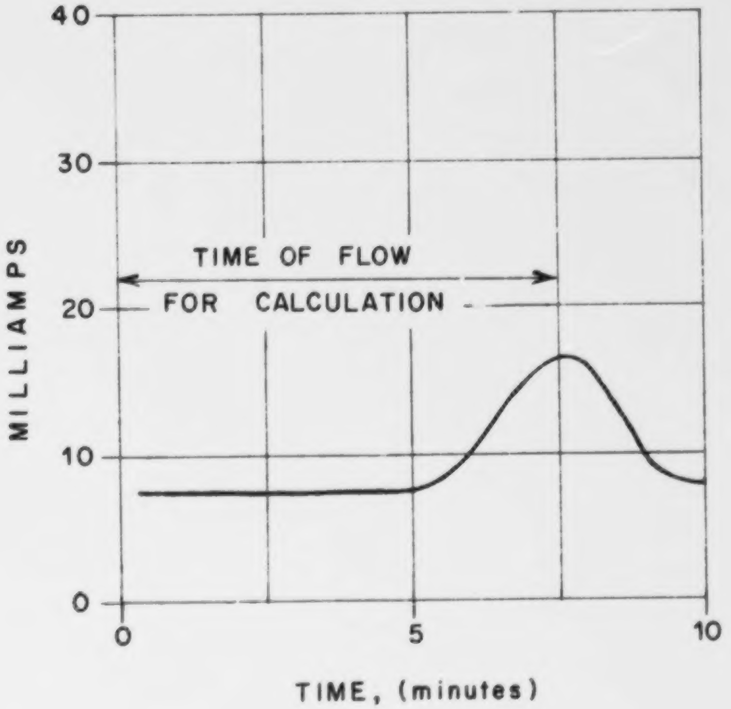
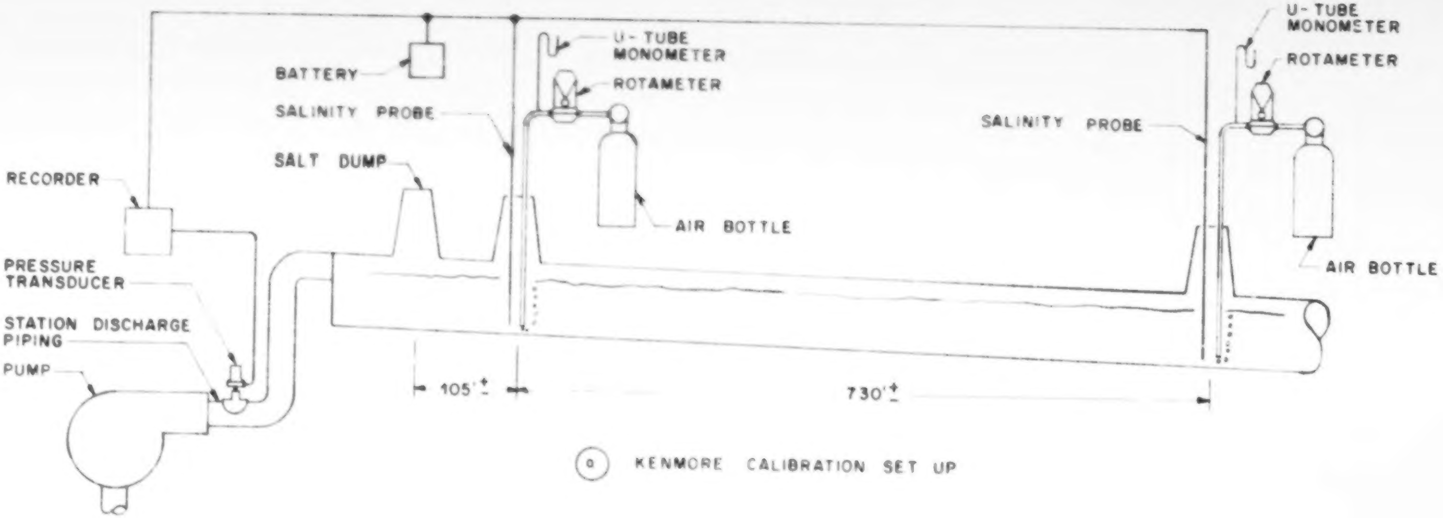


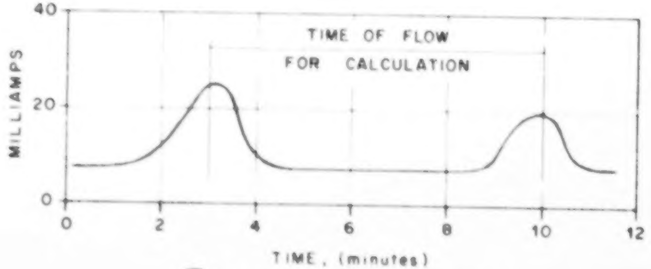
FIGURE H-2

SALINITY - TIME GRAPH

A major modification of the standard method of calibration force mains was made at the Kenmore pumping station. At this station, the time of flow in the force mains was too short to effectively measure the salt wedge transit time, so the calibration method was modified as shown in Figure H-3A. Air bottles, rotometers, and U-tube manometers were set up to measure the depth of flow in the sewer downstream from the pumping station. The method of sensing force main pressure was unchanged. The major modification used the second recorder pen to indicate the passing of the salt wedge. Three manholes downstream of the station were utilized -- one at the discharge of the force main; a second approximately 105 feet downstream; a third approximately 730 feet downstream. The probes were connected in series with a battery and wires strung from each probe back to the recorder. Milliampere flow in the line was then connected to the second recorder pen. Steady state flow volume was measured by the U-tube manometers and an air-bubbling system installed in each manhole. The pump was brought up to a stable pressure, the sewer line watched, and when both manometers were leveled out and a steady state of flow was read in the sewer, salt was injected at the upper manhole. Salt wedge passage at the first manhole began the time and the salt wedge passage at the second manhole ended the time. The time for each run was kept on the chart paper itself. A typical graph is shown in Figure H-3B.


BATTERY
U-TUBE MONOMETER
ROTAMETER
SALINITY PROBE
SALT DUMP
RECORDER
AIR BOTTLE
PRESSURE TRANSDUCER
STATION DISCHARGE PIPING
PUMP
U-TUBE MONOMETER
ROTAMETER
SALINITY PROBE
AIR BOTTLE
105'±
730'±

ⓐ KENMORE CALIBRATION SET UP



ⓑ SALINITY CONCENTRATION

FIGURE H-3

KENMORE FORCE MAIN CALIBRATION

Computations

The basic calculation of the steady state of flow Q, in cubic feet persecond, was determined by dividing the total volume in the force main between the point of salt injection and the salinity probe by the time required for the salt wedge to pass. Volume was determined from the as-built records of the total lengths of force mains and the inside diameter for the particular pipe material used. A small computer program determined the centroid of the passing salt wedge in relationship to time and the increased salinity as shown on the millimeter (Figure H-2).

The force main calibration test data for each station was tested to determine relationships between discharged pressure, static pressure, and discharge rate. An attempt was made to fit the data with a Hazen and Williams or a Darcy-Weisbach type equation of the form:

$$Q = K\ (P_d - P_s)^n$$

where:

Q - Rate of Discharge

P_d - Discharge Pressure

P_s - Static pressure

k,n - Constants

It was found that only the Interbay and South Mercer Island pumping station data followed the formula. Data from the other pump stations deviated radically. The inability to fit the data from the most pumping stations is probably due to the low level of turbulence encountered in these tests. The data indicates that the Reynolds number prevailing in the test area was in the transition range between laminar and full turbulent flow. The friction coefficient in this range is a function of discharge, making a Hazen and Williams type representation invalid. Even at the Interbay pumping station, the coefficient "n" in the above formula found by the least-square analysis of the data did not match the values associated with the Hazen and Williams formulas. Further analysis reveals that the data from all the force mains examined can be represented by the power series of the form:

$$Q = A_o + A_1\ P_d + A_2\ P_d^2 + A_3\ P_d^3 + \ldots.\ A_n\ P_d^n$$

Where the "A's" are constants, it was found that the first four terms of this expression are sufficient for the representation (i.e., a third order polynomial). Note that the static pressure may be ignored. The formulation actually used in the computer programming conditioned the input level pressure to indicate only the pressure rise above static and dropping the A_o value in the actual formula. The determination of the pump station discharge rate by the third order polynomial in the CATAD system involved a table-lookup of the polynomial coefficients for each pump station. The coefficients were determined by the least-square polynomial regression of discharge on pressure differential. The data from the two force mains at the Sweyolocken pumping station were combined so that only one set of coefficients need be used for that station. Likewise, the data for the two force mains at the Interbay pumping station were combined. Calibration of the Kenmore pumping station also allowed the use of just one formula for all three force mains. Calculation results are shown in Table H-2.

TABLE H-2
Station Discharge Equations

Station	Discharge Equation Q =	Static Pres. psi	Max. Pres. psi (Test)	Max. Q (Test) cfs
Matthews Park	$34.140x-5.153x^2+0.412x^3$	26.3	31.55	90.275
30th N. E.	$10.053x+0.500x^2-0.680x^3$	13.2	16.85	17.66
Kenmore	$5.334x-0.664x^2-0.166x^3$	10.58	12.85	6.843
Interbay	$25.801x-2.803x^2+0.171x^3$	10.90	16.9	90.817
Sweyolocken	$3.131x-0.244x^2+0.008x^3$	25.15 26.15	40.1	17.953
South Mercer Isl	$1.101x-0.084x^2+0.003x^3$	4.50	19.1	6.630
North Mercer Isl.	$3.443x-0.542x^2+0.034x^3$	38.15	45.0	9.185
Juanita Heights	$2.730x-0.326x^2+0.019x^3$	51.10	57.30	8.897
Bellevue	$2.840x-0.260x^2+0.010x^3$	26.85	35.00	11.167
Kirkland	$1.352x-0.133x^2+0.005x^3$	57.70	68.30	5.688

x = difference between total head and static head in psi

Q = discharge in cfs

Each station was tested to determine the relationship between the head loss and the discharge rate by the Darcy equation of the form:

$$h = f \frac{L}{D} \frac{V^2}{2g}$$

where:

h - Energy loss due to friction total

L - Pipeline length in feet

D - Pipeline diameter in feet

V - Velocity in feet per second

g - Gravitational acceleration in feet
per second

f - Friction loss coefficient

The friction loss coefficient "f" was developed for each station. A plot of the composite is shown in Figure H-4, and the formula for the individual friction factors for each station are listed in Table H-3.

TABLE H-3

DARCY EQUATION SUMMARY

Station	E^L/D	f Value
Juanita Heights	1736.54	0.01737+0.04557-V^2
Bellevue	1880.1	0.0199+0.06121-V^2
Kirkland	2862.9	0.01929-0.00747-V^2
Matthews Park	464.9	0.0134+0.00932-V^2
South Mercer Island	3179.5	0.0198+0.01764-V^2
North Mercer Island	1792.67	0.02123+0.02079-V^2
Kenmore	306.71	0.01219+0.09192-V^2
Interbay	987.75	0.01713+0.13315-V^2
Sweyolocken	2034.5	0.01393+0.03457-V^2
30th N. E.	133.36	0.02746+0.36418-V^2

The friction factor "f" was developed to provide a means of comparing the relative force main friction losses in each pumping station. In most stations with a sum of $\frac{L}{D}$ greater than 1000, the friction factor is approximately f=0.013. Exceptions are the Matthews Park and Sweyolocken pumping stations. The high friction factor coefficient for the 30th N. E. pumping station is explained by the station's age. This station's force main was installed in the early 1930's, and deterioration of the main is quite obvious. Using the Darcy equation in future calibration test runs, the indicated deterioration of the Municipality's force mains can be checked. It

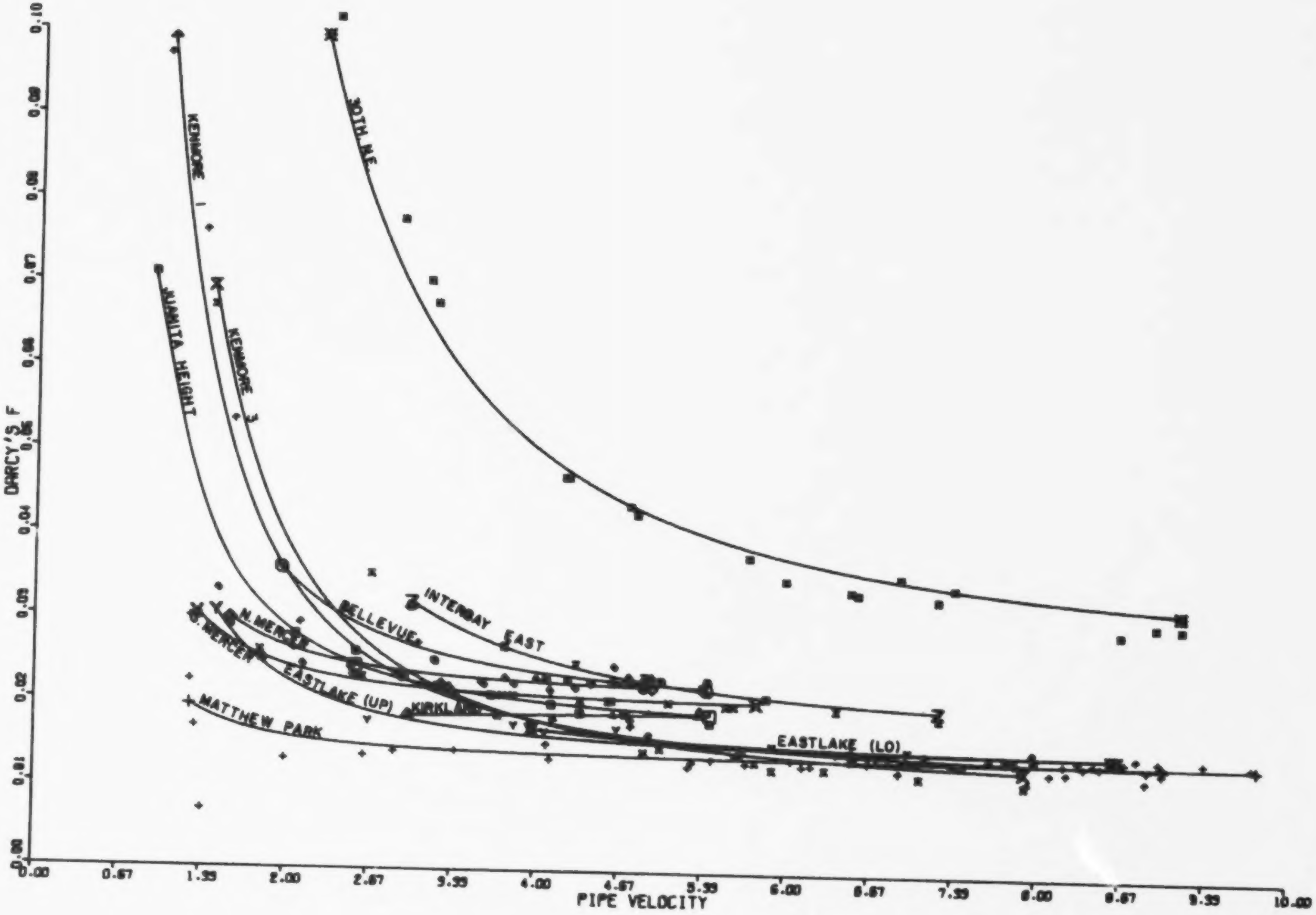


FIGURE H-4
DARCY "f" VALUES

was felt that the large number of factors considered in the Darcy equation rendered it unsuitable for use in the computer.

PERMANENT EQUIPMENT SELECTION

A typical force main pressure transmitter installation is shown in Figure H-5. The major components are listed in Table H-4.

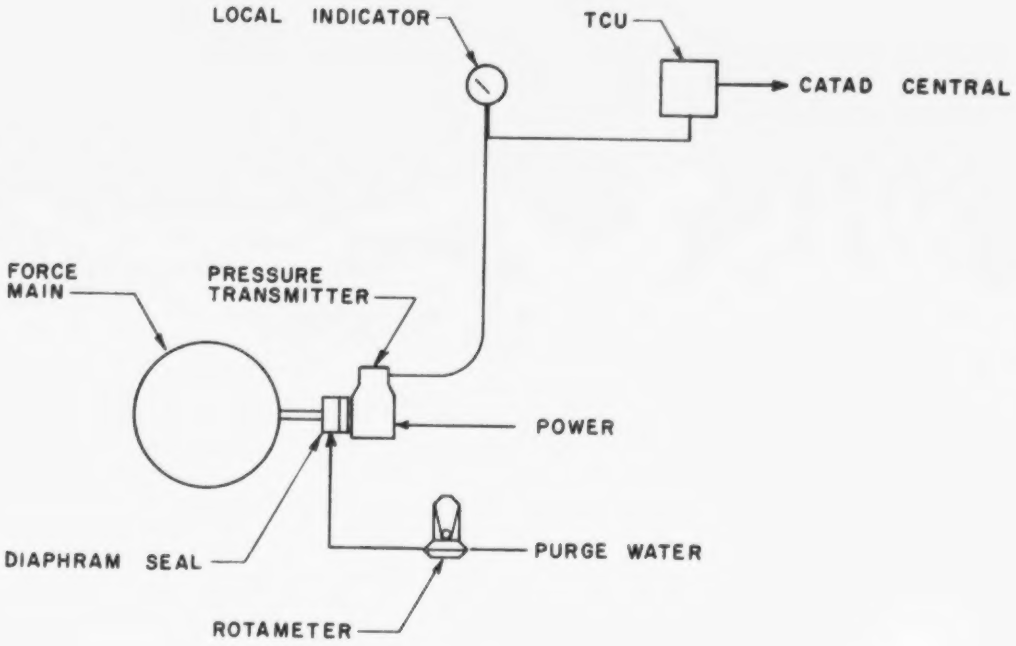

LOCAL INDICATOR
TCU
CATAD CENTRAL
FORCE MAIN
PRESSURE TRANSMITTER
POWER
DIAPHRAM SEAL
PURGE WATER
ROTAMETER

FIGURE H- 5

FORCE MAIN
PRESSURE TRANSMITTER
INSTALLATION

TABLE H-4

Component	Characteristics
Pressure Transmitter	Fischer and Porter Model 50 EP107 w/diaphragm seal
Local Indicator	1%, 250 degree scale, switchboard indicator, 4-20 ma equals 0-100%
Differential Pressure	3.3 GPH
Rotometer	Fischer and Porter Model 10A3135, 200 psig max.

The pressure transmitter is a standard industrial unit with a diaphragm seal which converts the transmitter's calibrated range to a 4-20 milliamp signal which is fed to the telemetry control unit in the station for transmission to the CATAD central office. A local indicator on the pumping station control panel provides visual indication of the force main pressure. Pressures and calibration ranges vary so much across the system that a standard 0 to 100 percent indicator was used. A mask showing relative flow was developed for each transmitter in the system. A sample mask is shown in Figure H-6.

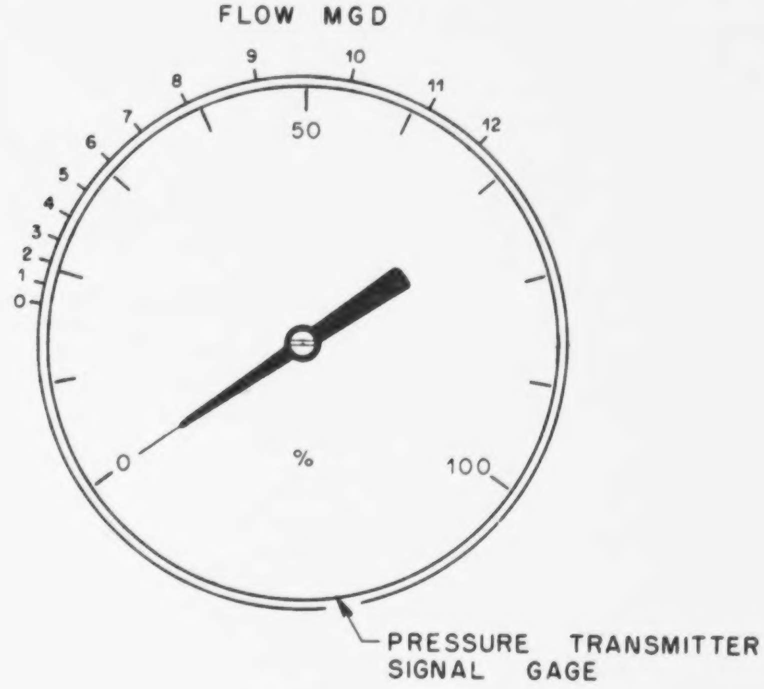


FIGURE H-6

TYPICAL FORCE MAIN CALIBRATION MASK

Each transmitter is water purged to maintain a clear opening to the force main and to prevent sewage solids from plugging the differential pressure rotometer sensing line. In many stations, booster pumps were required to bring the local system water pressure up to sufficiently overcome the maximum pressures which could be obtained in the force mains. Calibration adjustments of the individual transmitters in each station were made by modifying the test pressure transducer used in the force main calibration test runs. Metro's electrical department modified output of the test pressure transducer so that the pressure readings can be read directly on a standard digital voltmeter. Calibration was obtained to the nearest one-tenth psi.

APPENDIX I

DEXTER REGULATOR SIMULATIONS

The simulation model is based on the classic inflow-outflow-storage equation represented incrementally as follows:

$$S = S_2 - S_1 = \frac{I_1 + I_2}{2} \quad t - \frac{O_1 + O_2}{2} \quad t$$

where I = inflow
O = outflow
S = storage
t = time increment

Subscripts refer to the present and preceeding time increments. Storage and outflow (S_2 and O_2) are both unknown dictating a nested iterative solution for their values. The general solution procedure is indicated in Figure I-1.

Boundary conditions for solving the equation are:

1. Storage upstream of the regulator gate is approximated by the volume below a horizontal plane extending from the water surface at the station upstream to the intersection with the normal inflow depth or the Broad Street siphon, whichever gives the shorter length. This provides the condition for calculating water surface elevation upstream of the regulator station in any time increment when storage is known.

2. Regulator station outflow is computed from orifice equations or broad crested weir equations as appropriate. Station outflow is a function of water surface elevations upstream and downstream of the gate openings.

3. Water surface elevation downstream of the regulator station is a function of outflow. It is computed from the normal depth of flow over the overflow weir as applicable. The interrelation between outflow and downstream water surface elevation requires an iterative solution for these values when upstream water surface elevations and gate openings are known.

FLOW CHART OF DEXTER AVENUE REGULATOR SIMULATION MODEL

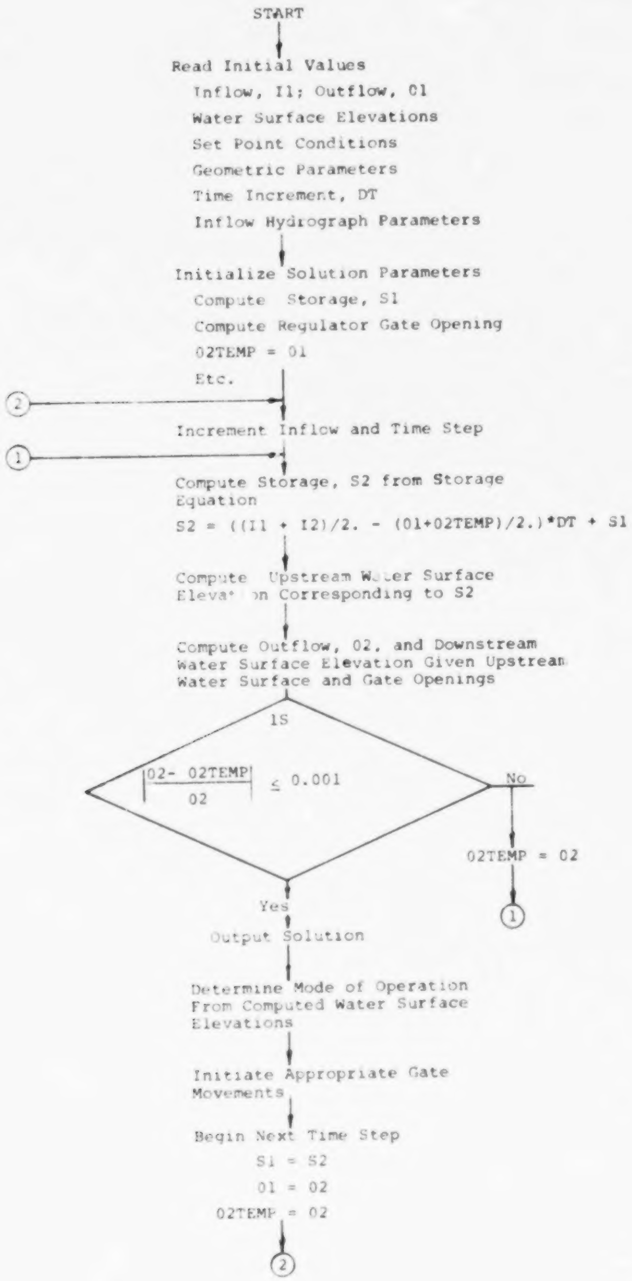

START
Read Initial Values
Inflow, I1; Outflow, 01
Water Surface Elevations
Set Point Conditions
Geometric Parameters
Time Increment, DT
Inflow Hydrograph Parameters
Initialize Solution Parameters
Compute Storage, S1
Compute Regulator Gate Opening
02TEMP = 01
Etc.
2
Increment Inflow and Time Step
1
Compute Storage, S2 from Storage Equation
S2 = ((I1 + I2)/2. - (01+02TEMP)/2.)*DT + S1
Compute Upstream Water Surface Elevation Corresponding to S2
Compute Outflow, 02, and Downstream Water Surface Elevation Given Upstream Water Surface and Gate Openings
IS
|02- 02TEMP / 02| ≤ 0.001
No
02TEMP = 02
1
Yes
Output Solution
Determine Mode of Operation From Computed Water Surface Elevations
Initiate Appropriate Gate Movements
Begin Next Time Step
S1 = S2
01 = 02
02TEMP = 02
2

FIGURE I-1

FLOW CHART OF DEXTER AVENUE REGULATOR SIMULATION MODEL

The general solution procedure in any time increment assumes an outflow rate and computes the corresponding storage and upstream water surface elevation using known values of the other parameters. Based on upstream water surface elevation and the gate openings, corresponding new values of outflow and downstream water surface elevations are computed. The new outflow rate is then compared with the assumed rate and a new iteration is begun if the two values do not match within a specified percentage. When a solution is reached for a given time increment, parameter values are output and appropriate gate movement initiated via a cascading series of FORTRAN IF statements depending on the computed water surface elevations and the setpoint conditions. The solution as a function of time may be plotted on a CALCOMP plotter.

Explicit solution stability criteria have not been determined, but is is known that a time increment of 3-sec or less is required. Although the simulation model has not been verified by comparison with field data, the simulated regulator station behavior is as expected and the results appear reasonable. The assumed triangular inflow hydrograph used in the simulation studies was defined by a rate of charge of inflow of 0.015 cfs/sec and a peak flow rate of 200 cfs. These are believed to exceed corresponding values in the real situation so that the computer simulation is conservative.

Setpoint conditions for Mode 3 operation were proposed after initial experience with the simulation model. These were modified on installation to provide a larger elevation difference between the regulator gate open and close position and to overlap the neutral positions. Computer simulation using the installed setpoint conditions revealed that this situation would result in Mode 3 upstream water surface fluctuation wide enough to cause inadvertent bypass gate tripping. This points out the need for computer simulation of station behavior under given setpoint conditions prior to installation. In general, the model revealed the following relationships:

1. Fluctuations in water surface elevation and storage upstream of the regulator gate, and in overflow rate downstream of the gate in Mode 3 operation are directly proportional to the dead band width between the gate open and close positions; and to the distance between the extremes of the dead band and the respective neutral positions. The speed of regulator gate motion may also have an effect. This factor was not examined.

2. Mode 3 neutral positions overlapping with the gate closing neutral position at a greater elevation than the gate opening neutral position cause excessively large upstream water surface elevation fluctuations. This

condition necessitates a lower elevation of the regulator gate open position to protect against inadvertent bypass gate tripping. Neutral positions should be set no more than one-third of the dead band width away from the respective gate open and close positions.

Further experience with the simulation model led to the following recommended Mode 3 setpoint conditions.

Setpoint	Recommended Elevations
Shift from Mode 2 to Mode 3	44.0
Regulator gate open position	44.0
Opening neutral position	43.9
Closing neutral position	43.7
Regulator gate close position	43.6
Bypass gate trip	44.6

Other setpoints were not modified.

The simulation model also determined the effect of the time required for the bypass gate to open fully on the maximum subsequent overflow rate to Lake Union. Reducing bypass gate speed spreads the resulting overflow hydrograph time, reducing the peak overflow rate and surge in the outfall. The original station design specified a 30-second opening period, which produces a very sharp overflow hydrograph and an extreme peak overflow rate.

Simulation studies revealed that a bypass gate opening period in excess of 10 minutes reduces the subsequent peak overflow rate to a value comparable to normal Mode 3 regulator operation. It was recommended that bypass gate speed be reduced to 6 inches per minute, providing an opening period of 11 minutes. Maximum simulated upstream water surface elevations with this gate speed ranged from 145.0 when the regulator gate was allowed to function normally to 146.2 when it was fixed in a nearly closed position to simulate gate malfunction. For reference, the regulator station gate room floor is at elevation 146.7.

TABLE J-1

MANUAL INVENTORY 03/07/74 PAGE 8

ITEM OR EQUIPMENT NAME		EQUIP. MODEL NO.	DESCRIPTION OF MANUAL/DOCUMENTATION	MANUAL CONTROL NO.	QUANTITY RECEIVED	QUANTITY ON ORDER
7440	L/P CONT	ROLL	7440 L/P CONTROLLER ESM	902363	0	50
7440	L/P CONT	ROLL	7440 L/P DIAG	704019-34	0	10
7440	LINE PRI	NTER	BUFFERED LINE PRINTER REF MANUAL	901014D	0	1
7440	LINE PRI	NTER	BUFFERED LINE PRINTER REF MANUAL	901014D	0	10
7440	LINE PRI	NTER	DPM SIGMA 2/3 COMP. LINE PRINTER TEST	901755	0	40
7440	LINE PRI	NTER	DIAG PROGRAM	SEE CONTR	0	
7440	LINE PRI	NTER	DIAGNOSTICS-M	901146	0	40
7440	LINE PRI	NTER	DIAGNOSTICS-P	704707-34	0	10
7440	LINE PRI	NTER	7440 BUFFERED L/P TECH MAN	901063	0	10
7440	LINE PRI	NTER	7440 L/P ESM	902364	0	50
7440	LINE PRI	NTER	7440 L/P REF MAN	901014	0	
7900	DEV SUB	CNTR	DEVICE SUB-CONTROLLER ESM	902381	0	50
800001		AYAA	CE MANUALS VOL. 1		0	
8001	SIGMA 2	CPU	SIGMA 2 REF MANUAL	900964F	0	7
8001	SIGMA 2	CPU	SIGMA 2 REF MANUAL	900964F	0	70
8001	SIGMA 2	CPU	CPU AUTO	704011-34	0	10
8001	SIGMA 2	CPU	DIAG PGM MAN FOR BINARY GENERATOR	901124	0	40
8001	SIGMA 2	CPU	DIAG PGM MAN FOR PERIPHERAL	900839	0	20
8001	SIGMA 2	CPU	DIAG PGM MAN FOR PERIPHERAL	900839	0	40
8001	SIGMA 2	CPU	DIAG PGM MAN SIGMA 2 AUTO	901007	0	40
8001	SIGMA 2	CPU	DIAG PGM MAN SIGMA 2/3 DIAG PGM MON	901650	0	40
8001	SIGMA 2	CPU	DIAG PROGRAM	704002-34	0	10
8001	SIGMA 2	CPU	DIAG PROGRAM	705299-34	0	10

Table J-2

MUNICIPALITY OF METROPOLITAN SEATTLE
COMPUTER DIVISION

SPARE PARTS INVENTORY

PAGE 1
08/29/73

EQUIPMENT ID MFG. PART NO.	DESCRIPTION	MFG.*	PRICE	UNIT	QUANTITY O.H.	QUANTITY MIN.
7160 CARD PUNCH						
5018675-00	INTERPOSER PLATE ASSEMBLY	X	60.00	EA	4	2
2013144-00	SENSING BRUSH	X	2.00	EA	30	10
2028223-00	TIMING BELT	X	4.50	EA	1	1
5014286-00	PUSHER BLADE	X	16.00	EA	1	1
5014505-00	ANTI-BACKUP BLADE	X	2.00	EA	5	2
920922	STRIKER BAR LOCATING FIXTURE	X	116.00	EA	1	0
921062	STRIPPER TIMING GAGE	X	115.00	EA	1	0
143447	MAGNETIC PICKUP	X	59.00	EA	1	1
143486	MAGNETIC PICKUP	X	84.00	EA	1	0
920315	BRUSH ADJUSTING GAGE	J	153.00	EA	1	0
921024	RRSP ADJUSTING TOOL	J	132.00	EA	1	0
143287	TIMING BELT	J	3.00	EA	1	0
5019629-00	PUNCH AND DIE ASSEMBLY	J	2908.00	EA	1	0
7162 CARD READER						
111344-021	O-RING,RUBBER SEAL	X	2.00	EA	6	2
136584-001	TIMING BELT	X	2.00	EA	1	0
136584-002	TIMING BELT	X	2.00	EA	1	0
136584-003	TIMING BELT	X	2.00	EA	1	0
136584-004	TIMING BELT	X	2.00	EA	1	0
7440 LINE PRINTER						
97A25947	TIMING BELT	N	4.00	EA	1	0
97A22167	TIMING BELT	N	5.00	EA	1	0
37 TELETYPE						
306280	TRIP LEVER	T	2.00	EA	1	1
151837	LEVER	T	1.00	EA	5	2
196066	PIN	T	0.05	EA	1	1
74882	SPRING	T	0.05	EA	1	1
196073	LEVER	T	7.00	EA	2	1

* H = HEWLET PACKARD L = LAMBDA
N = NCR T = TELETYPE
J = UNIVAC X = XEROX

APPENDIX K

RAINFALL STUDIES PROGRAM
SAMPLE OUTPUT

```
 RAIN STORM STUDIES  FROM 11/ 2/69 TO  7/ 1/73

INCREMENTS- TOTAL= 0.050   MAX.RATE= 0.010   AVG.RATE= 0.010
MINIMUMS  - TOTAL= 0.010   MAX.RATE= 0.010   AVG.RATE= 0.010
SEASON    - FROM MONTH,  1 TO MONTH 12
GAGES     - FROM GAGE 1 TO GAGE 6

  TOTAL
RAIN RANGE      N U M B E R   O F   S T O R M S   I N   R A N G E   A T
 FROM   TO      GAGE 1    GAGE 2    GAGE 3    GAGE 4    GAGE 5    GAGE 6
0.001- 0.050      189       154       140        95        88        30
0.051- 0.100       52        74        88        54        69        19
0.101- 0.150       49        41        41        35        36        11
0.151- 0.200       39        43        32        28        25         8
0.201- 0.250       21        30        30        31        28         9
0.251- 0.300       26        21        25        22        22        10
0.301- 0.350       13        16        23        14        17         3
0.351- 0.400       13        11        16         9        11         1
0.401- 0.450        5        13         8         7         9         3
0.451- 0.500        9        15        12         8         4         0
0.501- 0.550        7         7         5         7         5         1
0.551- 0.600        6         5         6         6         8         1
0.601- 0.650        4         8        11         4         5         2
0.651- 0.700        4         5         8         5         7         1
0.701- 0.750        6         6         7         3         6         1
0.751- 0.800        4         7         2         3         2         1
0.801- 0.850        1         3         6         3         6         1
0.851- 0.900        0         2         3         6         0         0
0.901- 0.950        0         3         2         4         2         0
0.951- 1.000        1         0         0         1         2         0
1.001- 1.050        0         0         2         1         3         0
1.051- 1.100        1         0         0         0         2         1
1.101- 1.150        1         1         1         1         0         0
1.151- 1.200        0         2         3         0         1         0
1.201- 1.250        0         0         0         0         1         1
1.251- 1.300        0         1         2         0         1         0
1.301- 1.350        0         0         0         3         1         0
1.351- 1.400        2         1         1         0         1         0
1.401- 1.450        1         3         1         0         0         0
1.451- 1.500        0         0         1         1         0         0
1.501- 1.550        0         0         0         0         1         1
1.551- 1.600        0         0         0         0         1         0
1.601- 1.650        0         0         0         1         1         0
1.651- 1.700        0         1         0         0         0         0
1.701- 1.750        0         1         0         1         0         0
1.751- 1.800        0         0         0         0         0         0
1.801- 1.850        0         0         0         0         0         1
1.851- 1.900        0         0         0         0         0         0
1.901- 1.950        0         0         1         0         0         0
1.951- 2.000        0         0         0         0         0         0
2.001- 2.050        1         0         1         1         0         0
2.051- 2.100        0         0         1         0         0         0
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  2.101- 2.150        0         0         0         0         0         0
  2.151- 2.200        0         0         0         0         0         0
  2.201- 2.250        0         0         0         0         1         0
  2.251- 2.300        0         0         0         0         0         0
  2.301- 2.350        0         0         0         0         0         0
  2.351- 2.400        0         0         0         0         0         0
  2.401- 2.450        0         0         0         0         0         0
  2.451- 2.500        0         0         0         0         0         0
  2.501- 2.550        0         1         0         0         0         0
  2.551- 2.600        0         0         0         0         0         0
  2.601- 2.650        0         0         0         0         1         1
  2.651- 2.700        0         0         1         0         0         0
                - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 TOTAL STORMS       455       475       480       354       367       107
 TOTAL  RAIN       81.49    107.92    117.68     89.60     98.39     26.85

  MAXIMUM
 RATE RANGE      N U M B E R  O F  S T O R M S  I N  R A N G E  A T
  FROM  TO       GAGE 1    GAGE 2    GAGE 3    GAGE 4    GAGE 5    GAGE 6
 0.001- 0.010      134       103        95        55        57        17
 0.011- 0.020       45        49        39        38        34         9
 0.021- 0.030       25        38        43        36        40        12
 0.031- 0.040       41        47        40        38        33         9
 0.041- 0.050       36        32        39        19        23         9
 0.051- 0.060       30        32        33        21        31        13
 0.061- 0.070       52        46        42        37        43        16
 0.071- 0.080       10        14        17        20        17         2
 0.081- 0.090       16        19        12        20        15         2
 0.091- 0.100       11        19        25         9        13         3
 0.101- 0.110        9        13        16         8        10         1
 0.111- 0.120       10        11        14         7         8         1
 0.121- 0.130        6         4         5         9         7         1
 0.131- 0.140        7         6         7         5         4         0
 0.141- 0.150        3        10        11         7         7         2
 0.151- 0.160        2         7         9         4         3         1
 0.161- 0.170        4         7         6         4         3         0
 0.171- 0.180        4         2         2         3         3         1
 0.181- 0.190        2         1         2         2         2         1
 0.191- 0.200        1         3         5         1         0         0
 0.201- 0.210        1         2         2         4         2         2
 0.211- 0.220        0         3         2         1         1         0
 0.221- 0.230        0         2         4         1         1         1
 0.231- 0.240        1         2         1         1         1         0
 0.241- 0.250        0         0         3         1         1         1
 0.251- 0.260        2         1         2         1         2         0
 0.261- 0.270        0         1         2         0         0         0
 0.271- 0.280        0         0         0         0         0         1
 0.281- 0.290        1         1         0         1         0         0
 0.291- 0.300        0         0         0         0         1         1
 0.301- 0.310        1         0         0         0         3         0
 0.311- 0.320        1         0         0         0         0         0
 0.321- 0.330        0         0         1         0         0         0
 0.331- 0.340        0         0         0         0         0         0
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0.341- 0.350        0        0        0        0        0        0
0.351- 0.360        0        0        0        0        1        1
0.361- 0.370        0        0        0        0        0        0
0.371- 0.380        0        0        0        0        0        0
0.381- 0.390        0        0        0        0        0        0
0.391- 0.400        0        0        0        0        0        0
0.401- 0.410        0        0        0        0        0        0
0.411- 0.420        0        0        0        0        1        0
0.421- 0.430        0        0        0        0        0        0
0.431- 0.440        0        0        0        0        0        0
0.441- 0.450        0        0        0        1        0        0
0.451- 0.460        0        0        0        0        0        0
0.461- 0.470        0        0        1        0        0        0

 AVERAGE
RATE RANGE     NUMBER OF STORMS IN RANGE AT
 FROM  TO      GAGE 1   GAGE 2   GAGE 3   GAGE 4   GAGE 5   GAGE 6
0.001- 0.010      166      138      126       89       84       23
0.011- 0.020       88      111      112       86       95       25
0.021- 0.030       78       76       83       63       77       28
0.031- 0.040       49       53       55       43       41        9
0.041- 0.050       25       37       29       25       24        7
0.051- 0.060       17       25       30       19       14        1
0.061- 0.070       19       21       23       22       22        7
0.071- 0.080        2        5        9        1        1        1
0.081- 0.090        4        5        1        2        1        2
0.091- 0.100        2        0        3        1        2        1
0.101- 0.110        2        2        4        1        4        2
0.111- 0.120        1        1        1        0        0        0
0.121- 0.130        0        0        1        0        0        0
0.131- 0.140        0        0        1        0        1        1
0.141- 0.150        1        0        0        0        1        0
0.151- 0.160        1        1        0        1        0        0
0.161- 0.170        0        0        0        1        0        0
0.171- 0.180        0        0        0        0        0        0
0.181- 0.190        0        0        0        0        0        0
0.191- 0.200        0        0        2        0        0        0
```

```
      FOR THE ABOVE PERIOD -
          AREA-WIDE STORMS, TOTAL =        183
          TRAVELLING OR FRONTAL, TOTAL = 140
          POCKET OR LOCALIZED, TOTAL =    182

   TOTAL
 RAIN RANGE       STORM PATTERN DISTRIBUTION
  FROM   TO    AREA-WIDE         FRONTAL           LOCALIZED
 0.001- 0.050    38                 53                     30
 0.051- 0.100    23                 20                     14
 0.101- 0.150    25                 11                     14
 0.151- 0.200    24                  9                     10
 0.201- 0.250     9                  7                      8
 0.251- 0.300    13                 12                      2
 0.301- 0.350    10                  3                      2
 0.351- 0.400     5                  7                      0
 0.401- 0.450     3                  1                      1
 0.451- 0.500     5                  4                      2
 0.501- 0.550     6                  2                      0
 0.551- 0.600     2                  2                      2
 0.601- 0.650     4                  2                      0
 0.651- 0.700     4                  0                      0
 0.701- 0.750     3                  1                      3
 0.751- 0.800     2                  2                      0
 0.801- 0.850     2                  0                      0
 0.851- 0.900     0                  0                      0
 0.901- 0.950     0                  0                      0
 0.951- 1.000     0                  1                      0
 1.001- 1.050     0                  0                      0
 1.051- 1.100     1                  0                      0
 1.101- 1.150     0                  1                      0
 1.151- 1.200     1                  1                      0
 1.201- 1.250     0                  0                      0
 1.251- 1.300     0                  0                      0
 1.301- 1.350     0                  0                      0
 1.351- 1.400     1                  1                      0
 1.401- 1.450     1                  0                      1
 1.451- 1.500     0                  0                      0
 1.501- 1.550     0                  0                      0
 1.551- 1.600     0                  0                      0
 1.601- 1.650     0                  0                      0
 1.651- 1.700     0                  0                      0
 1.701- 1.750     0                  0                      0
 1.751- 1.800     0                  0                      0
 1.801- 1.850     0                  0                      0
 1.851- 1.900     0                  0                      0
 1.901- 1.950     0                  0                      0
 1.951- 2.000     0                  0                      0
 2.001- 2.050     1                  0                      0
 2.051- 2.100     0                  0                      0
 2.101- 2.150     0                  0                      0
 2.151- 2.200     0                  0                      0
 2.201- 2.250     0                  0                      0
```

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2.251- 2.300    0                    0                         0
2.301- 2.350    0                    0                         0
2.351- 2.400    0                    0                         0
2.401- 2.450    0                    0                         0
2.451- 2.500    0                    0                         0
2.501- 2.550    0                    0                         0
2.551- 2.600    0                    0                         0
2.601- 2.650    0                    0                         0
2.651- 2.700    0                    0                         0
END PROGRAM
```

APPENDIX L
URBAN STORM DRAINAGE

Table L-1. PHYSICAL-CHEMICAL AND OILS ANALYSES

STATION	DATE	TIME	TEMP °C	DO *	BOD *	pH	Cl *	SO_4*	COND.	HEXANE EXT. OILS	TURB. JTU	COD*
VR1-1	730316	0800	9.5	11.8	0.5	7.8	14.0	34.	315	1.3	2.7	11
2	730316	0905	9.4	11.2	1.6	7.9	13.0		300	1.0	3.1	3
3	730316	0925	9.4	11.4	1.9	7.9	13.0		300	1.0	3.0	17
4	730316	0942	9.4	9.7	18.0	7.1	8.7		200	2.7	6.7	42
5	730316	0958	9.3	10.5	20.0	7.2	8.7	23.	133	12.8	44.0	62
6	730316	1014	9.2	10.6	7.4	7.3	8.7		108	4.1	28.0	53
7c	730316	1029	9.4	11.1								
		1140	9.7	11.0	1.3	7.1	4.2		130	5.0	23.0	47
SC4-1	730316	0800	9.6	10.2	1.3	7.7	10.5	78.	450	5.4	3.6	17
2	730316	0930	9.8	10.0	8.6	7.6	14.0		340	5.5	6.5	55
3	730316	0945	9.7	9.7	20.0	7.6	21.0		250	7.4	8.2	72
4	730316	1000	9.8	9.8	10.0	7.6	16.0		210	12.2	9.5	62
5	730316	1015	9.8	10.4	11.0	7.6	15.0	30.	120	6.5	8.4	67
6c	730316	1030	10.0									
		1115	10.1	10.3	8.2	7.8	9.9		100	7.4	8.1	46
10c	730316	1130	10.0	10.5								
		1215	10.0	10.3	4.2	7.1	10.8		105	3.5	7.4	42
CBD7-1	730316	0745	15.0	6.5	160.0	7.6	300.0	28.	420	11.0	61.0	300
2	730316	0815	12.5	6.0	16.0	7.7	96.0		420	12.0	51.0	300
3	730316	0830	13.0	7.0	17.0	7.6	57.0		310	9.7	87.0	250
4	730316	0845	12.5	6.8	31.0	7.6	48.0		260	19.0	89.0	410
5	730316	0900	11.2	8.5	27.0	7.6	27.0	22.	200	23.0	50.0	150
6	730316	0915	11.2	9.0	35.0	7.6	30.0		165	13.0	25.0	130
7	730316	0930	12.2	8.5	55.0	7.7	36.0		190	16.0	42.0	140
8	730316	0945	12.8	6.3	140.0	7.7	63.0	20.	250	20.0	53.0	480
9c	730316	1000	13.0	7.5								
		1015	15.0	7.5	68.0	7.7	60.0		300	22.0	52.0	190

* Concentration mg/l

Table L-2. NUTRIENT AND BACTERIAL ANALYSES

STATION	DATE	NITROGEN mg/1				PHOSPHOROUS mg/1		COLIFORMS ORGANISMS/100 ml		
		KJELD.	NH_3	NO_2	NO_4	TOTAL HYDR. PO_4	ORTHO	TOTAL	FECAL	FECAL STREP
VR1-1	730316	.60	.10	.02	1.10	.10	.06	2,200	150	
2	730316	.56	.10	.02	2.20	.11	.06	3,600	330	
3	730316	.68	.10	.03	2.20	.12	.06	5,900	500	
4	730316	1.70	.26	.11	1.70	.54	.15	16,400	450	
5	730316	1.70	.30	.13	.55	.22	.04	9,300	790	
6	730316	1.30	.22	.10	.40	.18	.05	6,300	640	
7c	730316	1.10	.10	.06	.60	.31	.06	11,000	600	
SC4-1	730316	.27	.08	.02	.15	.11	.05	260	2	
2	730316	.92	.26	.03	.60	.07	.03	45	2	
3	730316	1.40	.30	.04	.35	.09	.01	85	16	
4	730316	1.30	.26	.04	.75	.08	.02	95	75	
5	730316	1.10	.22	.04	.60	.15	0	160	2	
6c	730316	.74	.18	.04	.45	.16	0	85	10	
100	730316	.67	.10	.04	.40	.04	0	95	2	
CBD7-1	730316	31.00	7.00	.05	.40	4.40	.63	9,200,000	720,000	
2	730316	30.00	6.40	.10	.50	5.60	.72	over 10,000,000	2,900,000	
3	730316	19.00	4.60	.15	.70	2.70	.38	6,400,000	680,000	
4	730316	12.00	2.80	.10	.90	1.44	.23	3,200,000	2,800,000	
5	730316	8.70	2.00	.10	.70	1.20	.11	3,200,000	750,000	
6	730316	9.80	1.40	.10	.50	1.20	.69	over 10,000,000	920,000	
7	730316	14.00	3.60	.15	.50	1.30	1.30	6,500,000	850,000	
8	730316	16.00	4.80	.15	.50	1.30	.83	2,000,000	37,000	
9c	730316	19.00	3.80	.10	.40	4.00	1.00	2,000,000	180,000	

Table L-3. HEAVY METALS AND SOLIDS ANALYSES

		CONCENTRATION mg/1										
STATION	DATE	Cu	Pb	Fe	Hg	Cr	Cd	As	Zn	Set S.	SS	TDS
VR1-1	730316	.07	.10	.39	.0004	.01	.004	.05	.012	1.8	4	150
2	730316	.01	.10	.37	.0002	.01	.004	.05	.006	0.1	16	240
3	730316	.01	.10	.42	.0002	.01	.004	.05	.009	0.6	8	250
4	730316	.04	.22	1.40	.0002	.01	.004	.05	.061	0.1	80	210
5	730316	.03	.45	5.90	.0002	.01	.004	.05	.167	25.0	40	500
6	730316	.03	.39	1.40	.0002	.01	.004	.05	.154	41.0	76	130
7c	730316	.02	.39	1.30	.0002	.01	.004	.05	.065	19.2	88	130
SC4-1	730316	.20	.10	.57	.0002	.01	.004	.05	.150	0.1	8	352
2	730316	.16	.30	.75	.0002	.01	.004	.05	.330	0.1	28	340
3	730316	.13	.80	1.20	.0002	.01	.011	.05	.480	24.0	110	290
4	730316	.09	.82	1.60	.0002	.01	.004	.05	.460	24.0	40	250
5	730316	.15	.77	1.40	.0002	.01	.004	.05	.400	37.0	28	180
6c	730316	.05	.35	.75	.0002	.01	.007	.05	.250	0.1	24	160
10c	730316	.05	.27	.46	.0002	.01	.004	.05	.270	0.1	4	160
CBD7-1	730316	4.20	.10	.80	.0004	1.10	.010	.05	.240	60.0	100	330
2	730316	1.40	.10	.61	.0006	.70	.044	.05	.360	91.0	150	240
3	730316	.82	.20	.75	.0002	.72	.004	.05	.380	54.0	120	92
4	730316	.63	.57	2.30	.0004	.32	.004	.05	.510	120.0	160	32
5	730316	.37	.74	2.70	.0003	.16	.009	.05	.520	69.0	570	120
6	730316	.56	.45	1.80	.0009	.30	.004	.05	.430	41.0	110	120
7	730316	.56	.35	2.00	.0005	.40	.004	.05	.340	100.0	72	100
8	730316	.59	.22	13.00	.0018	.40	.004	.05	.420	21.0	160	170
9c	730316	.67	.15	1.90	.0002	.75	.004	.05	.310	---	90	140

APPENDIX M
SYSTEM PERFORMANCE PROGRAM

Table M-1. RAINFALL VS. OVERFLOW

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                    THIS TABLE IS TYPE. ALL STØRMS


     FØR MØDE--LØCAL CNTRL.
  TØTAL RAIN
  INCREMENTS FRØM LAST UP TØ. RAIN       ØVERFLØW--MG  NØ.ØVFLS.   NØ.EVENTS

            0.100   TØTAL=      6.252     17.753226    34.000        151
                      AVG.=     0.041      0.117571     0.225

            0.200   TØTAL=      7.891     53.442938    69.000         52
                      AVG.=     0.152      1.027749     1.327

            0.300   TØTAL=     11.627    364.701652   140.000         47
                      AVG.=     0.247      7.759610     2.979

            0.400   TØTAL=      6.903    281.325155   104.000         26
                      AVG.=     0.342     10.820198     4.000

            0.500   TØTAL=      6.621    195.536056    72.000         15
                      AVG.=     0.441     13.035737     4.800

            0.600   TØTAL=      8.254    381.923625   103.000         15
                      AVG.=     0.550     25.461575     6.867

            0.800   TØTAL=     12.952    414.774600   137.000         18
                      AVG.=     0.720     23.043033     7.611

            1.000   TØTAL=      7.101    258.613000    49.000          8
                      AVG.=     0.888     32.325625     6.125

            1.250   TØTAL=      2.264     33.132792     9.000          2
                      AVG.=     1.132     16.566396     4.500

            1.500   TØTAL=      6.913    688.101039    31.000          5
                      AVG.=     1.383    137.620208     6.200

            2.000   TØTAL=      1.770     28.536329     7.000          1
                      AVG.=     1.770     28.536329     7.000

            5.000   TØTAL=      2.432    173.064592     7.000          1
                      AVG.=     2.432    173.064592     7.000


     FØR MØDE--SUPV. CNTRL.
  TØTAL RAIN
  INCREMENTS FRØM LAST UP TØ. RAIN       ØVERFLØW--MG  NØ.ØVFLS.   NØ.EVENTS

            0.100   TØTAL=      2.594      2.980115    16.000         59
                      AVG.=     0.044      0.050510     0.271
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0.200   TOTAL=     0.310      0.200000    0.000        2
          AVG.=    0.155      0.100000    0.000

0.300   TOTAL=     1.750     14.300000    0.000        6
          AVG.=    0.292      2.383333    0.000

0.400   TOTAL=     3.710     20.100000    0.000       10
          AVG.=    0.371      2.010000    0.000

0.500   TOTAL=     2.840     14.300000    0.000        6
          AVG.=    0.473      2.383333    0.000

0.600   TOTAL=     3.410      7.100000    0.000        6
          AVG.=    0.568      1.183333    0.000

0.800   TOTAL=    14.410     79.000000    0.000       21
          AVG.=    0.686      3.761905    0.000

1.000   TOTAL=     4.780     10.800000    0.000        5
          AVG.=    0.956      2.160000    0.000

1.250   TOTAL=     6.080     43.800000    0.000        5
          AVG.=    1.216      8.760000    0.000

1.500   TOTAL=     1.310      0.200000    0.000        1
          AVG.=    1.310      0.200000    0.000

2.000   TOTAL=     1.660      1.800000    0.000        1
          AVG.=    1.660      1.800000    0.000

5.000   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000

    FOR MODE--AUTO. CNTRL.
TOTAL RAIN
INCREMENTS FROM LAST UP TO. RAIN      LOADING--PDS  NO.OVFLS.   NO.EVENTS

0.100   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000

0.200   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000

0.300   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000

0.400   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000

0.500   TOTAL=     0.000      0.000000    0.000        0
          AVG.=    0.000      0.000000    0.000
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0.600   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000

0.800   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000

1.000   TOTAL=    0.860      0.910841     8.000        1
          AVG.=   0.860      0.910841     8.000

1.250   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000

1.500   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000

2.000   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000

5.000   TOTAL=    0.000      0.000000     0.000        0
          AVG.=   0.000      0.000000     0.000
PERCENT REDUCTION SUPERVISORY VS LOCAL                                                                           OVERALL    WEIGHTED
 OVERFLOW VOL  0.570  0.435  0.768  0.696  0.403  0.169  0.129  0.421  0.000  0.000 -0.463  0.000     0.348       0.508
   NO. OVFLW. -0.204 -0.048 -0.395 -0.229 -0.567  0.163 -0.443 -0.796  0.000  0.000 -0.500  0.000    -0.351      -0.202

PERCENT REDUCTION AUTO VS LOCAL                                                                                  OVERALL    WEIGHTED
   OVRLFW VOL  0.385  0.989  0.975  0.984  0.775  0.000  0.000  0.972  0.000  0.000  0.000  0.000     0.947       0.970
   NO. OVFLW.  0.445  0.623  0.530  0.667 -0.979  0.000  0.000 -0.306  0.000  0.000  0.000  0.000     0.163       0.387

PERCENT REDUCTION SUPER+AUTO VS LOCAL                                                                            OVERALL    WEIGHTED
   OVRFLW VOL  0.778  0.712  0.872  0.840  0.589  0.565  0.564  0.696  0.000  0.000  0.269  0.000     0.656       0.776
   NO. OVFLW.  0.120  0.288  0.068  0.219 -0.323  0.561  0.253 -0.551  0.000  0.000  0.250  0.000     0.046       0.060
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APPENDIX M
SYSTEM PERFORMANCE PROGRAM

Table M-2. RAINFALL VS. LOADING

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              THIS TABLE IS TYPE. NØ3.N

    FØR MØDE--LØCAL CNTRL.
TØTAL RAIN
INCREMENTS FRØM LAST UP TØ. RAIN      LØADING--PDS  NØ.ØVFLS.   NØ.EVENTS

          0.100   TØTAL=      0.150       8.600000     0.000          4
                   AVG.=      0.038       2.200000     0.000

          0.200   TØTAL=      3.110      18.400000     0.000         18
                   AVG.=      0.173       1.022222     0.000

          0.300   TØTAL=      5.510      78.400000     0.000         21
                   AVG.=      0.262       3.733333     0.000

          0.400   TØTAL=      6.030      39.400000     0.000         18
                   AVG.=      0.335       2.188889     0.000

          0.500   TØTAL=     10.080      92.400000     0.000         22
                   AVG.=      0.458       4.200000     0.000

          0.600   TØTAL=      6.700      37.600000     0.000         12
                   AVG.=      0.558       3.133333     0.000

          0.800   TØTAL=     17.960     126.300000     0.000         26
                   AVG.=      0.691       4.857692     0.000

          1.000   TØTAL=      8.820     103.300000     0.000         10
                   AVG.=      0.882      10.330000     0.000

          1.250   TØTAL=      4.290      55.400000     0.000          4
                   AVG.=      1.073      13.850000     0.000

          1.500   TØTAL=      2.950       3.300000     0.000          2
                   AVG.=      1.475       1.650000     0.000

          2.000   TØTAL=     10.820     168.900000     0.000          6
                   AVG.=      1.803      28.150000     0.000

          5.000   TØTAL=      2.050      16.100000     0.000          1
                   AVG.=      2.050      16.100000     0.000

    FØR MØDE--SUPV. CNTRL.
TØTAL RAIN
INCREMENTS FRØM LAST UP TØ. RAIN      LØADING--PDS  NØ.ØVFLS.   NØ.EVENTS

          0.100   TØTAL=      0.030       0.100000     0.000          1
                   AVG.=      0.030       0.100000     0.000
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      0.200   TOTAL=     6.123      23.800579   57.000       41
                AVG.=     0.149       0.580502    1.390

      0.300   TOTAL=     3.244      23.371093   54.000       13
                AVG.=     0.250       1.797776    4.154

      0.400   TOTAL=     4.158      39.437520   59.000       12
                AVG.=     0.346       3.286460    4.917

      0.500   TOTAL=     0.425       7.781411    8.000        1
                AVG.=     0.425       7.781411    8.000

      0.600   TOTAL=     2.189      84.603548   23.000        4
                AVG.=     0.547      21.152137    5.750

      0.600   TOTAL=     4.994     140.562348   79.000        7
                AVG.=     0.713      20.080335   11.286

      1.000   TOTAL=     2.737      56.171719   33.000        3
                AVG.=     0.912      18.723906   11.000

      1.250   TOTAL=     0.000       0.000000    0.000        0
                AVG.=     0.000       0.000000    0.000

      1.500   TOTAL=     0.000       0.000000    0.000        0
                AVG.=     0.000       0.000000    0.000

      2.000   TOTAL=     3.665      83.479643   21.000        2
                AVG.=     1.833      41.739822   10.500

      5.000   TOTAL=     0.000       0.000000    0.000        0
                AVG.=     0.000       0.000000    0.000

   FOR MODE--AUTO. CNTRL.
TOTAL RAIN
INCREMENTS FROM LAST UP TO. RAIN     OVERFLOW--MG  NO.OVFLS.   NO.EVENTS

      0.100   TOTAL=     0.360       0.028611    2.000       16
                AVG.=     0.022       0.001788    0.125

      0.200   TOTAL=     0.612       0.043251    2.000        4
                AVG.=     0.153       0.010813    0.500

      0.300   TOTAL=     1.277       0.954286    7.000        5
                AVG.=     0.255       0.190857    1.400

      0.400   TOTAL=     1.092       0.530644    4.000        3
                AVG.=     0.364       0.176881    1.333

      0.500   TOTAL=     0.940       5.873000   19.000        2
                AVG.=     0.470       2.935000    9.500
      0.600   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      0.800   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      1.000   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      1.250   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      1.500   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      2.000   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000

      5.000   TOTAL=      0.000        0.000000      0.000        0
                AVG.=     0.000        0.000000      0.000
PERCENT REDUCTION SUPERVISORY VS LOCAL
 LOADING        0.955  0.902  0.362  0.082  0.433  0.622  0.226  0.791  0.368  0.879  0.936  0.000          OVERALL      WEIGHTED
   NO. OVFLW.   0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000            0.596         0.382
                                                                                                             0.000         0.000
PERCENT REDUCTION AUTO VS LOCAL
   OVRLFW VOL   0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000          OVERALL      WEIGHTED
   NO. OVFLW.   0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000            0.000         0.000
                                                                                                             0.000         0.000
PERCENT REDUCTION SUPER+AUTO VS LOCAL
   OVRFLW VOL   0.377  0.951  0.681  0.541  0.716  0.811  0.613  0.895  0.684  0.939  0.368  0.000          OVERALL      WEIGHTED
   NO. OVFLW.   0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000            0.798         0.000
                                                                                                             0.000         0.000
END PROGRAM
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